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Fluvial periglacial environments, climate and vegetation during the Middle Weichselian in the northern Netherlands with special reference to the Hengelo Interstadial

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Abstract

A six meters thick fluvial sequence of Weichselian Pleniglacial age has been studied in a building site south of Grouw (northern Netherlands). Twelve ^{14}C-dates provide a chronological framework covering the period from 43 to 35 ka BP. Two main sedimentary facies (channel and overbank) have been distinguished. The channel facies reveals strong episodic flow related to snow-melt peak discharges. The overbank facies were formed by crevasse splays and in backswamp and lake environments. At least seven periglacial levels have been found in the highly cryoturbated overbank facies.

Ice-wedge casts levels indicate the repeated occurrence of permafrost and a mean annual temperature around -4,5°C during the 43-35 ka BP period. A close relation has been established between the periglacial levels (permafrost formation and degradation) and sedimentation phases. The Middle Pleniglacial sedimentary environments and the shrub tundra vegetation were found to have been fairly stable and the thresholds for major changes in river pattern and vegetation were not exceeded during the investigated period. A short-term climatic improvement with a 2 to 3°C temperature rise could be established between 38,7 and 36,9 ka BP (Hengelo Interstadial). In this period the permafrost regionally degraded resulting in increased thaw-lake development and predominantly lacustrine deposition. A subtle northward shift of the continuous-discontinuous permafrost boundary is suggested for this period.

Introduction

The fluvial architecture of a basin fill is the result of several, often interacting factors. These main controlling factors are the accommodation space, governed bytectonics and base level/eustatic level, and sediment supply governed by climate and hydraulics of the fluvial system (Schlager, 1993). Because these factors interact and operate simultaneously, it is often hard to establish the effect of a single factor from ancient fluvial sequences. For instance, changes in the local hydrological regime of the system (by lateral migration or avulsion) and changes in climate may both result in a similar sedimentary sequence. This holds true for changes of the permafrost in the floodplain as well. Permafrost degradation may be caused by local (hydrological) changes (e.g. erosion of the river bank, forest fires) or by climatic changes (Burn & Smith, 1988).

Especially for the Late Glacial period, changes in the fluvial dynamics of river systems have been related to changes in climate and vegetation (Bohncke & Vandenberghe, 1991; Kasse et al., 1994). For the Weichselian Pleniglacial the effects of climate and climatic changes on the fluvial system are less well understood. Earlier studies by Van der Hammen et al. (1967) and Zagwijn (1974) focussed on the chronostratigraphy, vegetation and climate of the Pleniglacial deposits. Lithological and pollen composition changes, were attributed to changes in climate. In this way, three interstadials (Moershoofd, Hengelo, Denekamp) were defined, which were separated by colder stadials. According to these authors, the interstadials were characterized by organic accumulation, the stadials were dominated by sand deposition. Later Van Huissteden (1990) corrected this rather rigid depositional model in his major study concerning the Pleniglacial tundra river environments. He demonstrated that peat/gyttja formation occurred throughout the whole Pleniglacial and no periods of intensified organic production could be established, except for the 42-40 ka BP interval (Van Huissteden, 1990, p. 129). This indicates that alternations of organic beds and clastic beds were generally not controlled by climate, but by intrinsic changes in the river system only. Climate (temperature) was found to be fairly constant during the Pleniglacial with a mean annual temperature around -1°C (Ran & Van Huissteden, 1990). Only one colder interval around 40 ka BP (-5°C) was established, based on the presence of ice-wedge casts.

The general aim of this study is the reconstruction of the fluvial depositional environments, vegetation and climate during the Weichselian Pleniglacial in the northern Netherlands. The fairly continuous accumulation in the studied basin during a well-dated interval (43-35 ka BP) enables detailed reconstruction of short-term changes in environment, vegetation, fluvial dynamics and climate. The interaction of the sedimentary environment and permafrost in the floodplain, as expressed by sedimentary and periglacial cyclicity, is studied. An attempt is made to distinguish between intrinsic and climate-induced changes in the fluvial system.

The location of the studied pits is in the northern Netherlands, in the province Friesland, 2 km south of the village Grouw (Figure 1; N 53°04'45", E 5°49'54"). During the construction of the highway Heerenveen-Leeuwarden a tunnel was built under the Prinses Margriet canal. The entrance and exit lanes to the tunnel offered two large and up to 15 m deep exposures in Middle and Late Pleistocene deposits.

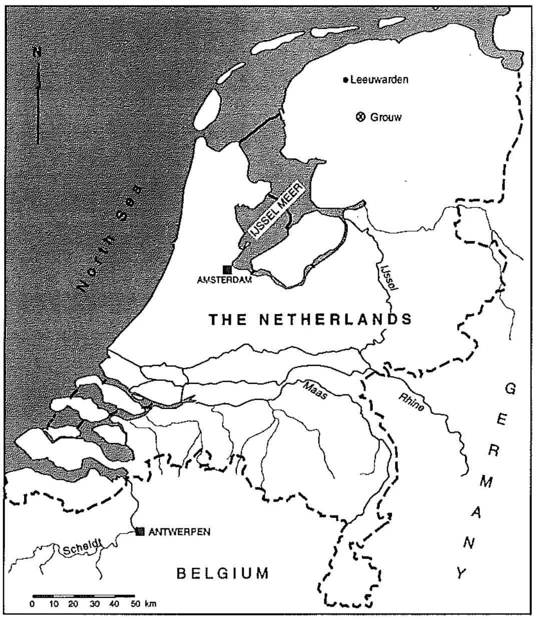


Figure 1
Map of the Netherlands with the location of the investigated exposure at Grouw.

Geological setting

The exposures were situated in the coastal plain of central Friesland (Figure 2). The topographic surface is approximately 0.5 - 1 m below sea level. At this locality the Holocene sequence consists of clays and peats of the Westland Formation, which formed due to the Holocene sea level rise and associated marine transgression and rise in groundwater. The Holocene deposits overlie a Pleistocene sequence of Weichselian (Twente Formation), Eemian (Asten Formation) and Saalian (Drente Formation) age (De Groot et al., 1987). The Saalian sediments are of glacial origin (till). They were deposited during the Older Saalian Glaciation (Ehlers et al., 1984). The Eemian and Weichselian sediments occur in the headwater of a local catchment, probably of the Boorne river. This catchment was studied earlier by Cnossen & Zandstra (1965). The small river drained the higher Saalian till regions in the south and east (see Figure 2). The depth contours of the top of the Pleistocene surface

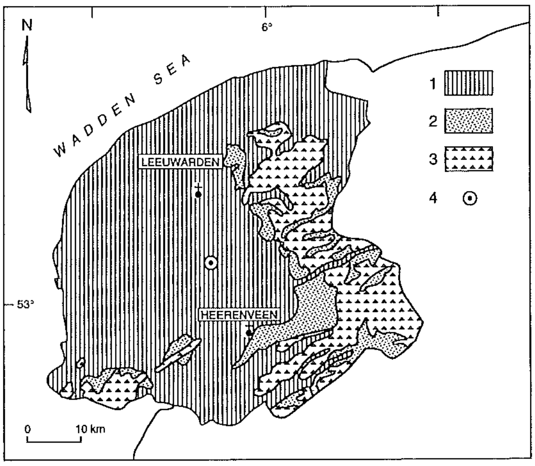


Figure 2
Generalized geological map of the province Friesland.

1 Holocene deposits;
2 Weichselian, mostly aeolian, sands;
3 Saalian till;
4 Exposures Grouw.

indicate that the exposure is situated in a northnorthwest draining valley (De Groot et al., 1987).

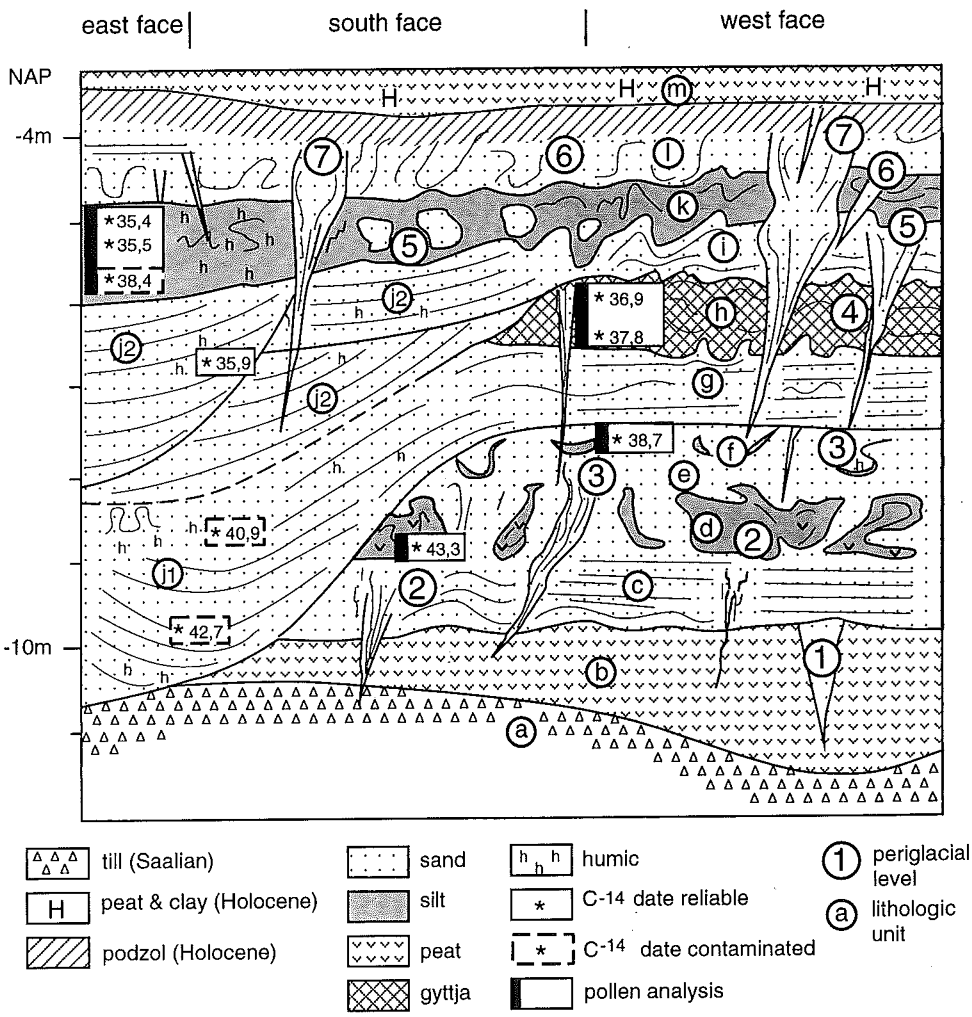
A compiled lithological section of the southern exposure is given in Figure 3. Unit a (Saalian till), unit b (Eemian peat and gyttja) and unit m (Holocene peat and clay) have not been studied in detail and are represented only schematically.

Unit a is a greenish gray clay with dispersed pebbles and cobbles (basal till) of late Saalian age. The top is decalcified by soil formation after ice retreat and/or during the Eemian. The upper 3.5 m of the till displays well-developed horizontal platy structures due to ice-lens growth after ice retreat or during the early Weichselian.

The overlying Eemian unit b fills a channel structure. In the deepest part of the channel unit b consists of a coarse-detrital gyttja and wood peat covered by a humic silt or gyttja. In the upper part of the channel a peat layer is present which also extends outside the channel.

Units c up to and including l consist of Weichselian Pleniglacial, mostly fluvial, sediments. The Weichselian sequence consists of fine sands alternating with humic silts and fine-detrital gyttja. The sequence is characterized by ice-wedge cast levels and associated periglacial involutions.

Figure 3
Composite section of the Pleniglacial sequence at Grouw, southern exposure (strong vertical exaggeration).
^{14}C-dates taken by the Geological Survey have not been included.



Sedimentary environments and facies during the Middle Pleniglacial

The depositional environments described below date from the Weichselian Middle Pleniglacial, approximately from 45 to 35 ka BP. The validity of the 14C-dates is discussed in detail in the following paragraph, but the results are used here to create a time frame for the different environments. The Pleniglacial sedimentary sequence has been divided in two main sedimentary facies: an overbank facies (Figure 3: units c,d,e,f,g,h,i,k,l) and a stacked channel facies (unit j). In the exposure south of the canal both facies were present and were studied in more detail. The contact between the two facies, this is the channel margin, has a SSE-NNW orientation. In the exposure north of the canal the channel facies dominated.

Overbank facies

The fluvial overbank units (Figure 3: units c,d,e,f,g,h,i,k,l) show a complete, 6 m thick, sequence formed by aggradation of the palaeo-Boorne river system in the 43 to 35 ka BP interval. The sequence consists of five, vertically stacked sedimentary cycles. Each cycle is made up of a fining-upward sequence of fine sand overlain by sandy silt, peaty silt or gyttja (Figure 3: c-d, e-f, g-h, i-k, l). The sediment sheets of these 5 cycles overlie each other concordantly and erosion at the start of a new cycle seems to have been of minor importance. The lateral transition of the overbank facies to the channel facies is preserved only for the units g and i. The corresponding channel facies of the sandy overbank units c and e have been eroded during a later phase of channel activity before channel subunit j1 was deposited.

Periglacial structures (ice-wedge casts, cryoturbations) are very common in the overbank facies (Figure 4: photo A,B,C). Unfortunately, the periglacial activity has strongly deformed the sedimentary structures in the sand units. Besides by the sedimentary structures the sedimentary environment of the fine-grained units (silt, gyttja) can be inferred from the lithology, grain-size analysis and their palaeobotanical content.

The overbank facies have been subdivided into crevasse splay deposits (units c,e,g,i,l) and backswamp and lake sediments (units d,f,h,k).

Crevasse splay deposits

The sand units (Figure 3: units c,e,g,i,l) are in general characterized by parallel lamination. Small-scale cross-lamination is of minor importance. The only weakly cryoturbated unit c has been studied in more detail (Figure 5: photo A,B,C). Even horizontal lamination, wavy parallel lamination and small-scale cross-lamination are present. In the upper part of sand unit c (Figure 5: photo A) the horizontally laminated sets occur at the base of short (10 cm) fining-upward sequences, while small-scale current ripple cross-lamination occurs in the upper part of the fining ups. Since both bedding types are found in one fining-upward sequence, it is concluded that the horizontal lamination is of fluvial origin as well. The short fining-upward sequences then represent a change in current velocity from upper flow regime, horizontal lamination (coarser grained sand) into lower flow regime ripple cross-lamination (finer grained sand). The current ripples are locally clearly visible by the draping of organic detritus over the ripple forms or in the ripple troughs (Figure 5: photo B). The sedimentary structures described above point to strong fluctuations in current velocity which may be associated with the process of crevasse splay deposition of sand outside the river channel.

The wavy parallel lamination in unit c, especially in the lower part, has a small-scale, crinkly appearance on a mm-scale. The individual laminae are indistinct. This bedding type is attributed to adhesion of dry aeolian sand on a moist surface in adhesion ripples or warts (Rust, 1972, p. 231-232; Ruegg, 1983, aeolian subfacies B; Schwan, 1986, stratification types 5 and 6).

The bedding types described above indicate shallow water deposition and subaerial exposure during the deposition of overbank unit c. This is supported by the presence of frost cracks (Figure 5: photo C) within unit c, which were formed by strong cooling of the depositional surface.

The (often strongly deformed) sedimentary structures and the grain size of units e, g, i and l indicate a more or less comparable depositional environment as unit c. Deposition occurred predominantly in a shallow fluvial, crevasse splay environment. Units e, g and i do not reveal any structures related to aeolian processes. Unit g is somewhat coarser grained and contains thin humic silt layers which both point to fluvial deposition. Unit l is, in the lower part, characterized by strongly cryoturbated, fine sand with several low-angle truncation levels, probably formed by shallow running water. The upper part of unit l is less deformed and horizontally laminated with alternating bedding of fine sand and silty fine sand. This facies resembles, sedimentologically, aeolian sand sheet deposits.

Backswamp and valley lake sediments

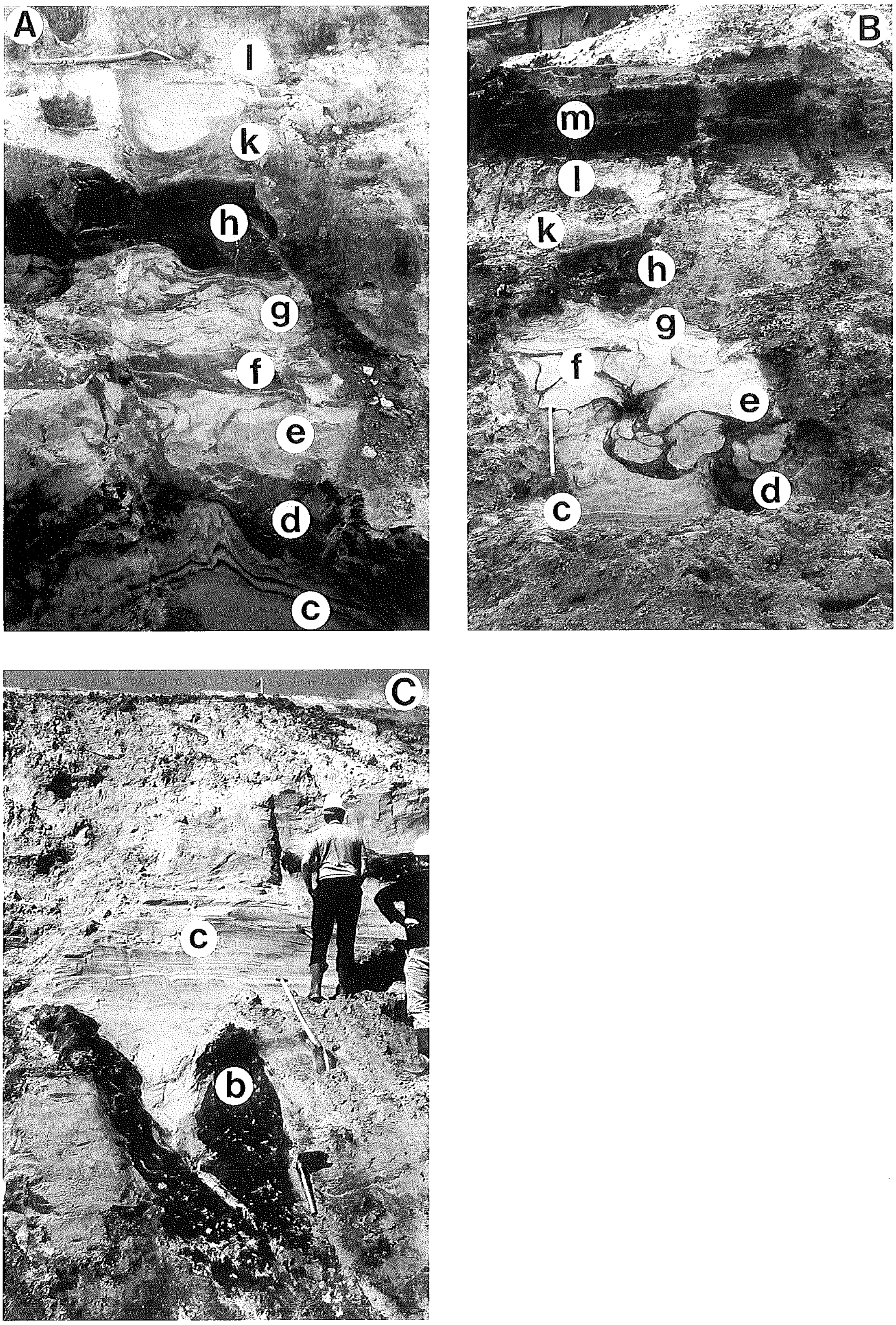
The fine-grained overbank units (Figure 3: d,f,h,k) form the upper parts of fining-upward sequences indicating that they were formed in the final phase of fluvial deposition or in standing water conditions. The lithology as well demonstrates that deposition occurred in low-energy environments.

The peaty character of silt unit d (43,3 ka BP) points to a (semi)terrestrial depositional environment. The high content of *Carex* seeds in the macroremains supports this interpretation. The environment was probably characterized by marshy backswamp conditions beside the channel. The high silt content can be explained by the sedimentation of suspended material in the backswamp environment during high water. The fine-grained unit f

(38,7 ka BP) probably was formed in a comparable environment as unit d, although the higher silt content shows that the environment was more frequently flooded or more proximal to the sediment source.

Fine-grained unit h (37,8-36,9 ka BP) is of special interest, because it extends throughout the overbank facies as a distinct, fairly thick (60-90 cm), slightly sandy, fine-detrital gyttja layer, in general only moderately affected by cryoturbation. Its thickness and fine-detrital nature indicate a considerable water depth during deposition.

Figure 4
Photographs of the Pleniglacial overbank facies. Photo A and B: Overbank sequence with periglacial levels and fining-upward sedimentary cycles of coarse-grained units (c,e,g,(i),l) and fine-grained units (d,f,h,k). Spade for scale is 120 cm. Photo C: Base of the overbank sequence with truncated ice-wedge cast (periglacial level 1) penetrating Eemian unit b.



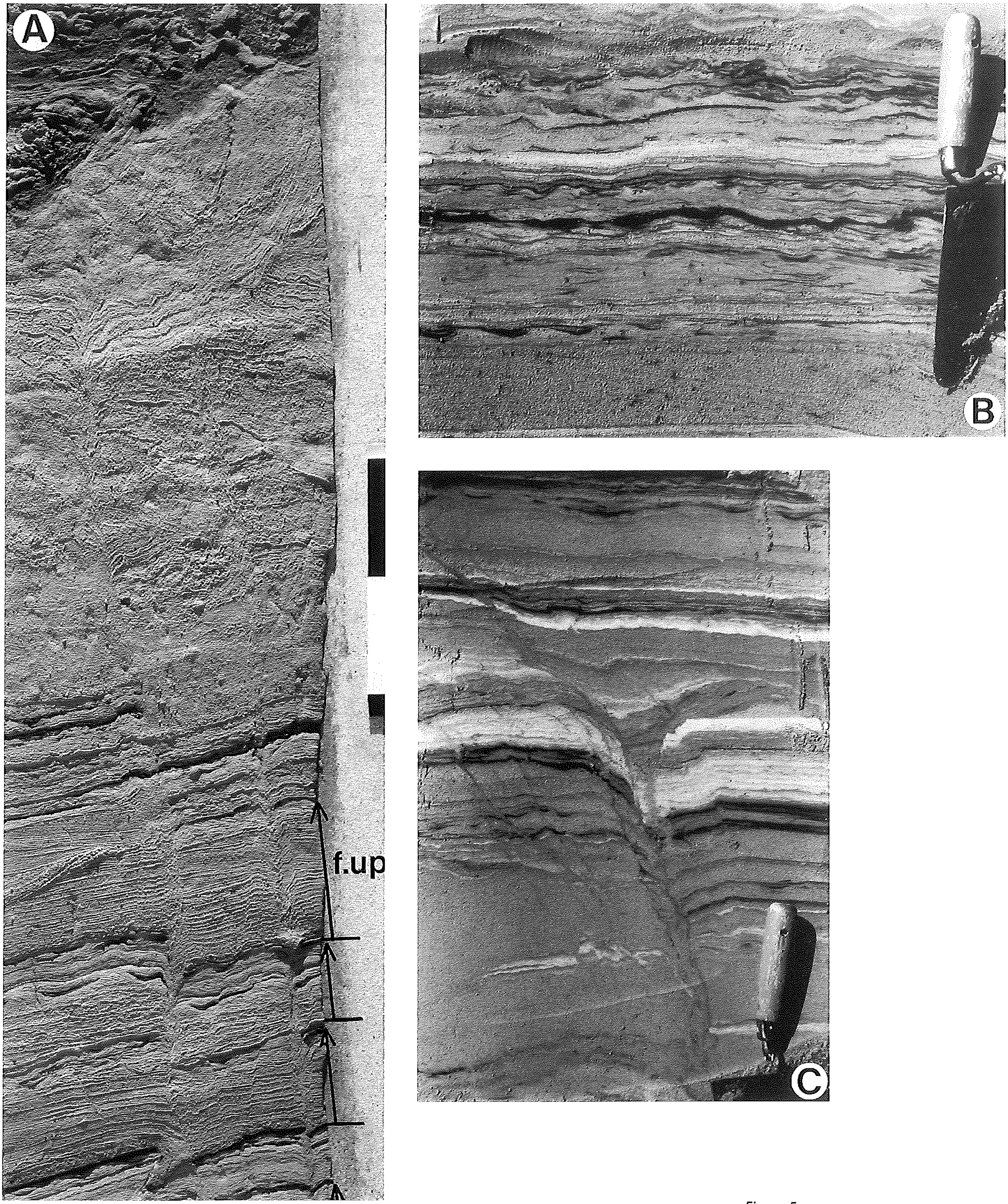


Figure 5

Photographs of the overbank facies: sand unit c. Photo A: Lacquer peel (110 cm high) of the upper part of unit c, characterized by thin fining-upward sequences (f.up) pointing to shallow water crevasse splay deposition. Note the frost cracks attached to the base of the overlying fine-grained unit d. Photo B: Detail of the sedimentary structures in unit c. The humic silt flasers and drapes (black color) accentuate the small-scale current ripple cross-lamination. Photo C: Frost crack within unit c pointing to periodic aerial exposure of the surface in between successive phases of crevasse splay deposition.

The uniform composition of the gyttja points to rather stable environmental conditions. A hydroseral succession toward peat formation has not occurred or the peat has been eroded during the onset of the overlying new - sedimentation cycle (unit i).

The genesis of this rather deep and stable lake is somewhat puzzling, because it formed and persisted for a 1000 radiocarbon years, just after the deposition and thus vertical accretion of sandy overbank unit g. Directly below the gyttja layer very clear involutions are present (Figure 6: photo A,B). Such structures in a periglacial sequence are generally attributed to the melting of ground ice. These cryoturbations are overlain by the gyttja layer which contains non-disturbed, horizontal, discontinuous sand laminae. The succession described above may be interpreted as a thermokarst phenomenon with thaw-lake

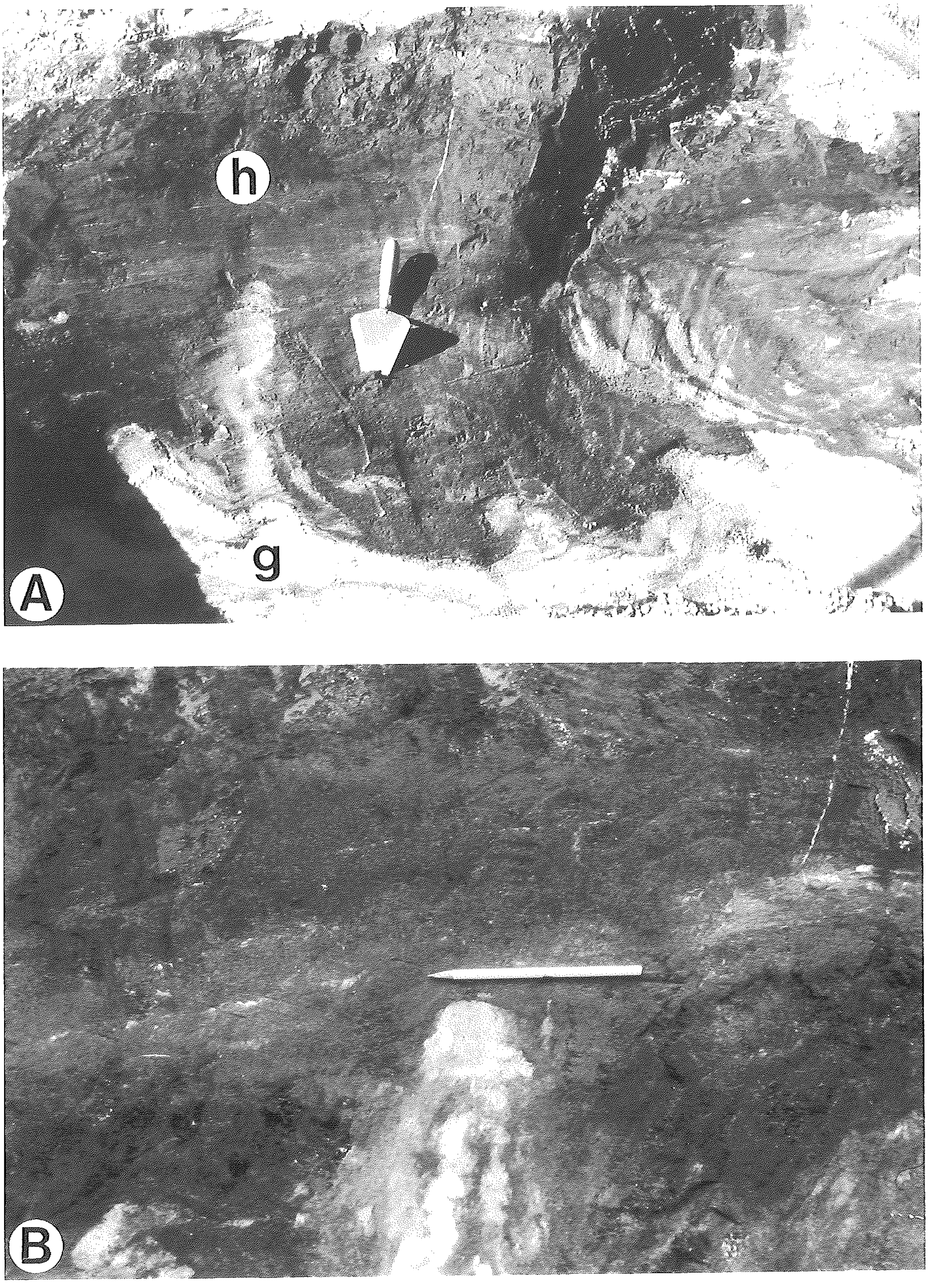


Figure 6
Photo A: Involutions at the base of unit h, attributed to permafrost degradation. Photo B: Close up of photo A. The gyttja with horizontal sand laminae (near the pencil) is interpreted as a thaw-lake infilling on top of strongly deformed sediments.

development. Van Huissteden (1990, p. 70-74) found a comparable succession of the same age in the Dinkel valley. He mentions the presence of an erosional surface between the cryoturbated sediments and the overlying undisturbed lacustrine units. According to Hopkins & Kidd (1988), who studied thaw-lake sedimentation in recent periglacial environments, the erosional boundary reflects the phase of permafrost degradation and thaw-lake formation. In our case the boundary between the involuted sediment and the horizontally laminated gyttja is clearly visible, but does not seem to be erosive (Figure 6: photo B at the pencil). The absence of peat lumps, which normally fall into the thermokarst lake by shore retreat (Hopkins & Kidd, 1988), may be due to the fact that the thaw lake developed in a clastic unit (unit g). The climatological implications of unit h are discussed below.

The depositional environment of unit k (35,5-35,4 ka BP) is different from units d, f and h. Unit k overlies and fills an abandoned channel (Figure 9: photo D). The humic, sandy silt and gyttja indicate low current velocity deposition gradually changing into lacustrine conditions. Water depth was certainly larger than during the deposition of units d and f. The presence of Ranunculaceae (*Batrachium*) and *Myriophyllum* spp also points to open water conditions. The high organic matter content of unit k is only found in the east face of the southern exposure (Figure 3), where

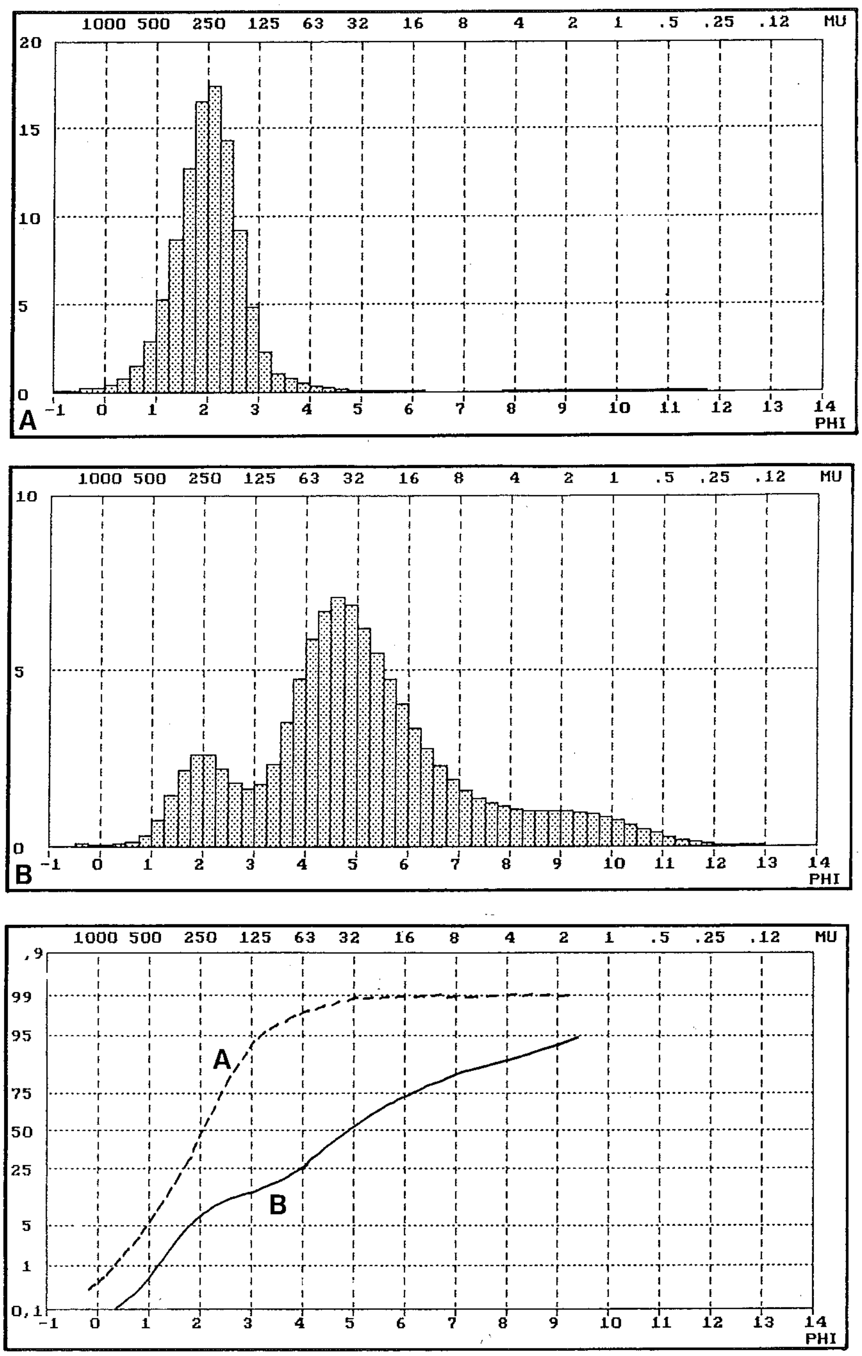


Figure 7
Grain-size histograms and cumulative curves of the overbank deposits (A: coarse overbank; B: fine overbank).

the unit is thick and in a lower topographic position. In the south and west face unit k has a greenish gray color. This lateral change in organic content and color is in our opinion the result of post-sedimentary oxidation of the organic matter by late Weichselian and Holocene soil formation.

Grain-size characteristics of the overbank sediments

The overbank sediments (units c,d,e,f,g,h,i,k,l: 18 samples) have been subdivided in two distinct groups and an intermediate one:

i. The first group is relatively coarse grained (240 to 265µm), practically without silt and clay (> 97% sand fraction) (Figure 7: histogram A, curve A). The samples resemble the coarse channel fill samples described below. They represent deposition of the coarse suspension load at the maximum of a crevasse flood. The coarsest grains did not reach the overbank position while the finer fraction was transported moredistal from the source.

ii. The second group is a bimodal sandy silt (modal values 240 to 250µm and 31 to 39µm). The silt contentis between 50 and 66%, but the clay content is low (4,5 to 7%) (Figure 7: histogram B, curve B). This sediment represents the deposition of suspension load at the waning stage of the flood. The low clay content may be surprising when compared for instance with overbank sediments from the Maas at Maastricht-Belvédère which contain high amounts of clay (Vandenberghe et al., 1993). The deposition of clay is firstly dependant on the existence of lakes with standing water after a flood and secondly on the distance from the sediment source. Apparently at Grouw such standing water conditions were not frequently present after the flood flow stopped and the water level dropped. Only unit h has a high clay content of c. 25%. The presence of a lake environment is confirmed by the sedimentary structures and the palaeobotanical record of unit h.

   The granulometric composition of the fine part of this bimodal deposit resembles quite well the grain size of loesses (Vandenberghe & Krook, 1981; Vandenberghe et al., 1985). Therefore, it is possible that this fine sediment derives from a windblown loess which has been transported in suspension by the river and as such has been redeposited. Also in the Twente area Van Huissteden (1990) could demonstrate an aeolian origin for part of the redeposited alluvial sediments.

iii. A number of samples show characteristics intermediate between the coarse-grained and fine-grained groups. Their principal modal value is always 190 to 240µm and the clay content below 3,5%, but the amount of silt may vary between 5 and 32%. They may represent transitional phases between high water stage and low water stage deposition or marginal positions in the overbank depression.

   One sample is of a different grain size association. The modal value is 155µm with 7% silt and 1,4% clay. The sand is moderately sorted with a small coarse tail. Its position is within the cryoturbated lower most part of unit c, just below a pebble layer which truncates periglacial level 1. The sedimentary structures thus give no clue to an interpretation of its origin. The granulometric composition, however, is equal to the one of aeolian coversands (e.g. Vandenberghe & Krook, 1981; Van Huissteden, 1990). It is argued below that the pebble layer and periglacial level 1 date from the late Early Pleniglacial. Aeolian activity from that period has also been reported previously from the southern Netherlands (Vandenberghe & Krook, 1985). No other samples resemble coversands, so that aeolian activity in the overbank environment at Grouw has been very local.

Channel facies

Unit j (Figure 3) contains all the characteristics of a channel sequence: the large-scale geometry of the unit, the sandy material, the general fining-upward trend, the erosional contacts at the margin and the large-scale and small-scale cross-bedding. The large-scale unconformities in unit j enable the distinction of at least two channel subunits (subunit j1 and j2). These subunits are time-equivalent with the overbank units g and i, which formed between 38,7 and 35,5 ka BP. Channel sediments equivalent with the overbank units c, e and l have not been found and therefore the channel sequence is less complete than the overbank series.

Large-scale sedimentary sequence of unit j

Unit j as a whole reveals a fining-upward sequence of about 6 m. However, unit j was not formed by one channel, since it consists of a stacked series of channel units, separated from each other by large-scale unconformities (Figure 3: subunits j1 and j2). Locally, periglacial features (involutions) have been found in the top of subunit j1, which indicates that permafrost could develop occasionally. This means that part of the floodplain was inactive for some time, until it was flooded again and the involutions were truncated forming a unconformity. These erosional levels show that unit j was formed by different channel generations (j1 and j2), which correspond in time with the deposition of respectively the overbank units g and i.

The general fining-upward trend in unit j points to a gradual decrease in energy during the successive generations of channels at this spot. This, however, does not imply a regional decrease of the fluvial activity in the time span between 38,7 ka (Figure 3: unit f) and 35,5 ka BP (Figure 3: unit k). The unconformities within channel unit j2 (Figure 3) suggest a shift of successive channels to the north. A ^{14}C-date from the northern exposure indicates that around 36,2 ka BP the channel had its main axis in the northern exposure, leaving the southern exposure in a more channel marginal position (see discussion below). The top of the sequence shows that after 35,5 ka BP, the investigated exposures occurred outside the active channel belt and only lacustrine and overbank sediments, strongly affected by periglacial activity, were formed (Figure 3: unit k and l).

The dates also show that the channel remained more or less in the same position between 38,7 and 35,5 ka BP. Also before 38,7 ka BP the channel must have been nearby, since the overbank units c and e resemble the overbank units g and i. Such a stability of the channel is characteristic for an anastomosing river system. The concept of anastomosing rivers during the Pleniglacial was postulated earlier by Van Huissteden (1990) in the Dinkel valley.

Falling stage modifications of sedimentary structures

Channel subunit j1 is incised in Pleniglacial fluvial sediments (Figure 3: units c,d,e,f) and in the Eemian peat (unit b). In Figure 8 (photo A) the erosive character of the Weichselian channel is well expressed. The channel has eroded the Eemian peat and has scoured the infill of an ice-wedge cast, which may belong to periglacial level 1, 2 or 3. After the scouring, the ice-wedge cast was refilled with coarse, gravelly sand at the base of a large-scale cross-bedded set. Especially in the northern exposure the channel has incised into the Saalian till. Large amounts of coarse detritus and wood fragments at the base of the Weichselian sequence testify the erosion of the Eemian (Figure 8: photo B).

In the basal 1,5 m of subunit j1, fine to medium sand (150-420 μm) with large-scale cross-bedding is common. Current direction is in general to the northwest (296°, n=4 in the south exposure; 332°, n=10 in the north exposure). This direction is in close agreement with the SE-NW direction of the channel left bank. Locally, the cross-bedded sets reveal well-developed reactivation surfaces

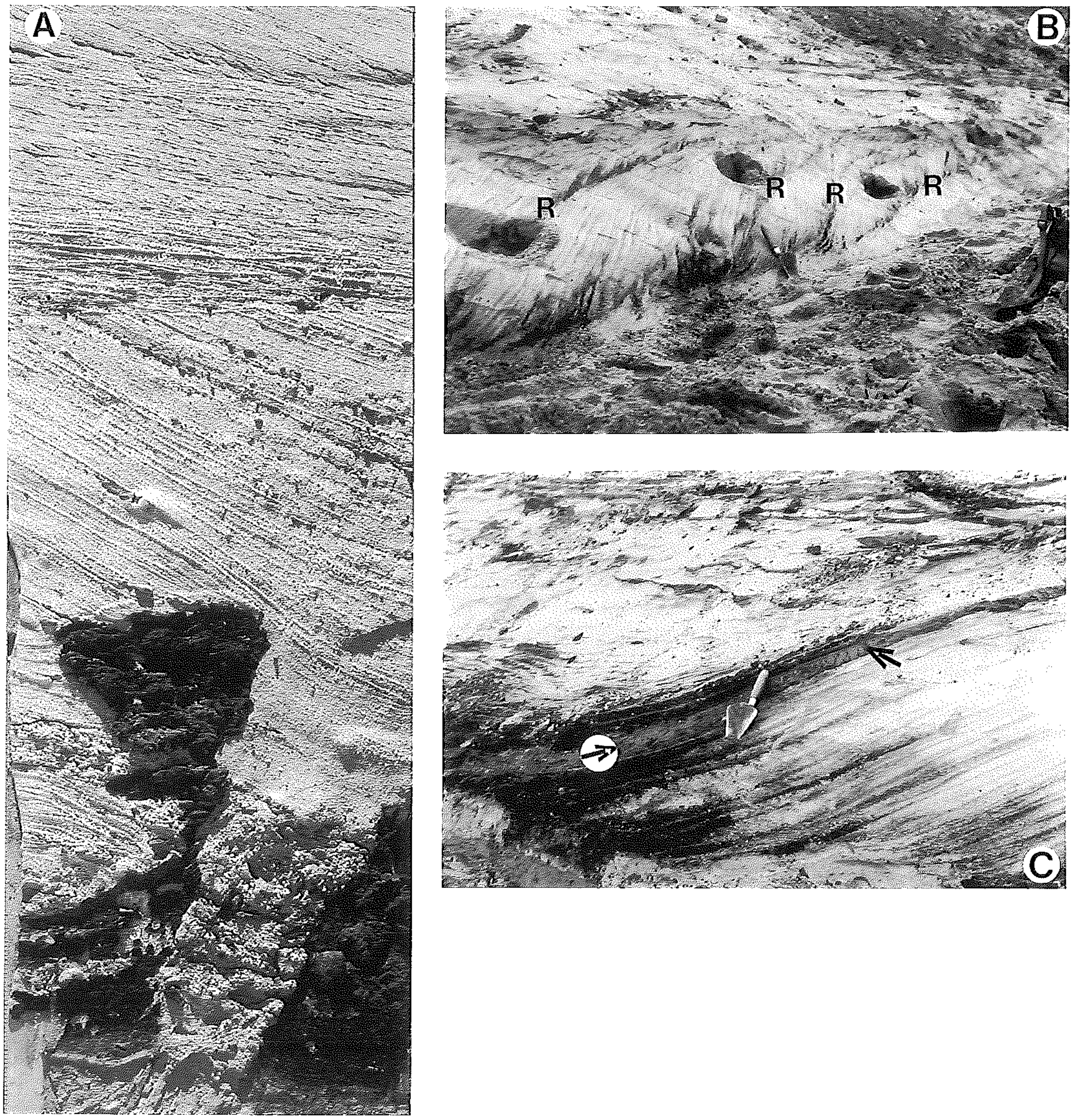


Figure 8
Photographs of the Pleniglacial channel base (subunit j1).

Photo A
Lacquer peel (110 cm high) from the erosive base of the channel sequence. Note the eroded Eemian peat clast and scour and fill of the ice-wedge cast.

Photo B
Large-scale cross-bedding at the channel base with several reactivation surfaces (R) formed by low water stage modifications of the bar.

Photo C
Large-scale cross-bedding at the channel base with reworked Eemian organic matter in the foresets (black). Note the silt drape (gray) on the foresets (see arrows) deposited at the falling water stage.

(Figure 8: photo B). The tabular cross-bedded set consists of high-angle foreset bundles, separated by low-angle erosional surfaces (reactivation surfaces). These structures are interpreted as falling stage features (Collinson, 1970). At high water stages, sand was transported over the bar crest and was deposited in asymptotic foresets at the lee side of the bar. Lowering of the water level may have led to a change in the current direction parallel to the crest, which may have reduced the angle of the foreset slope by erosion (falling stage modifications of the bar). During the following water level rise and high water stage the bar was reactivated and the erosional surface was covered by new high-angle foresets. According to Jones (1977) these internal sedimentary structures may give some information about the discharge regime of the river system. Since this cross-bedded set occurs at the base of the channel sequence j1 it can be concluded that the discharge variations were large. During high water

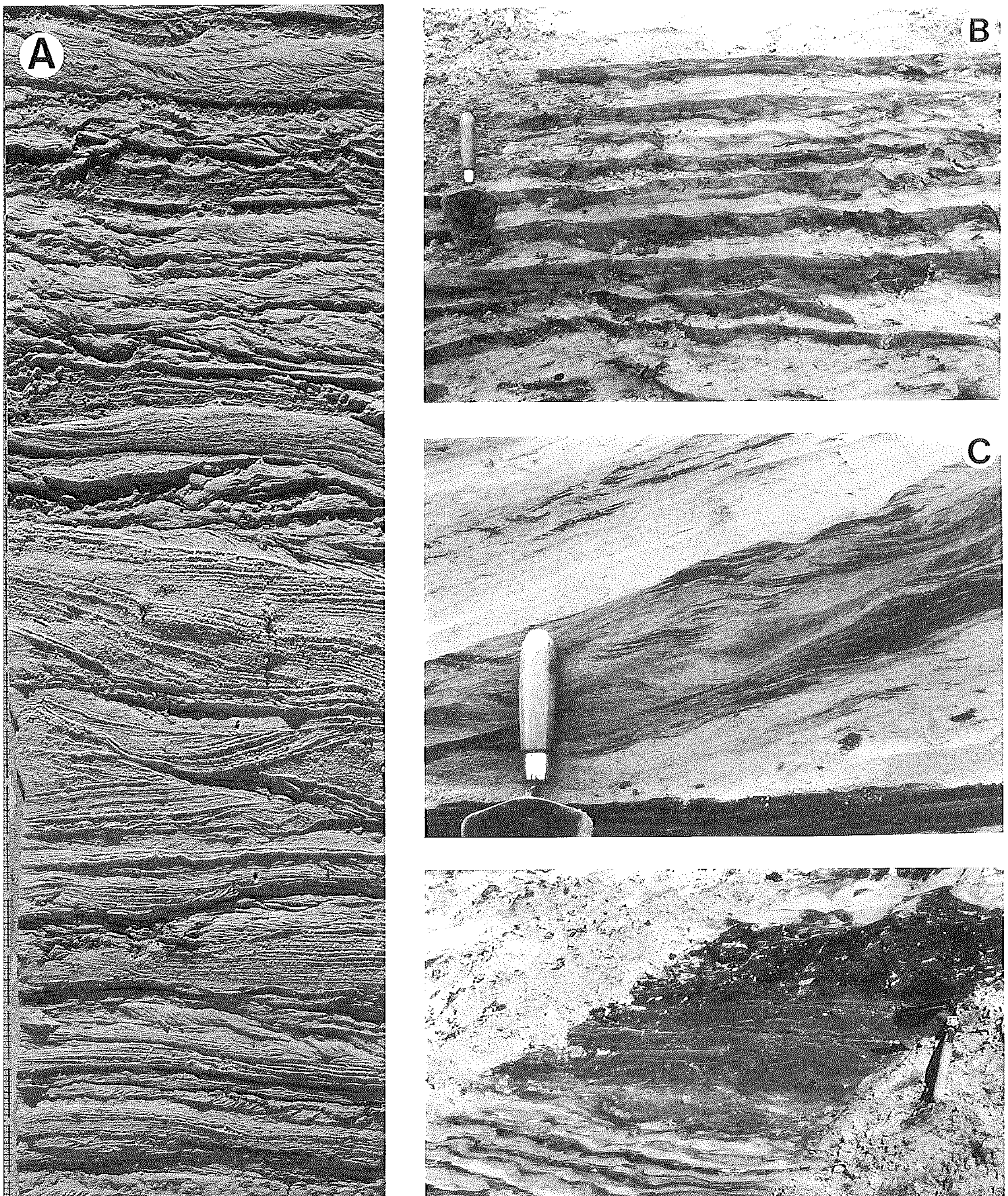
Figure 9
Photographs of the Pleniglacial channel fill (unit j).

Photo A
Lacquer peel (110 cm high) with well-developed alternations of high water, horizontal laminated sands and low water, current ripple laminated fine sand and silt (subunit j2).

Photo B
Alternations of high water stage sand (white) and low water stage silt (dark), illustrating the peaked character of the snow melt water river (subunit j2).

Photo C
Close up of a silty fine sand layer showing climbing ripple cross-lamination formed during a falling water stage in the channel (subunit j1).

Photo D
Fining-upward sequence (white is sand; black is silt and gyttja) in the upper part of the channel (unit j2-k), illustrating the gradual transition of a fluvial into a lacustrine environment. Spade for scale is 50 cm.



stages the bar was covered by water, but water depth above the bar is difficult to establish. In the 38,7-37,8 ka BP interval not only the channel subunit j1 was formed but also the overbank unit g. The latter is situated approximately 2 to 3 m above the bar surface. The reactivation surfaces on the other hand indicate that during the low water stages the channel was almost dry or filled by shallow water of 1 m or less. From these estimations water level fluctuations of at least 2 to 3 m can be established.
The reactivation surfaces are the result of water stage fluctuations and they point to strongly fluctuating discharges of the Pleniglacial river system between 38,7 and 37,8 ka BP. This idea is supported by the presence of silt drapes on the slipface of the bar (Figure 8: photo C). The deposition of such fine-grained drapes is also associated with the falling water stage in the channel. Besides foreset reworking (reactivation surfaces), fines may be deposited from suspension in the sheltered areas in front of the bar (Rust, 1972). In the following high water stage the clay/silt drape has been preserved by foreset progradation.

Episodic flow structures

Higher in the channel sequence, in both subunits j1 and j2 (38,7-35,5 ka BP), the sands are fine grained and intercalated with many sandy, humic silt layers. Low-angle channel fill cross-bedding, horizontal bedding and smallscale cross-lamination are the dominant bedding types (Figure 9: photo A and B). The boundaries between the sand and silt beds are usually very sharp. These

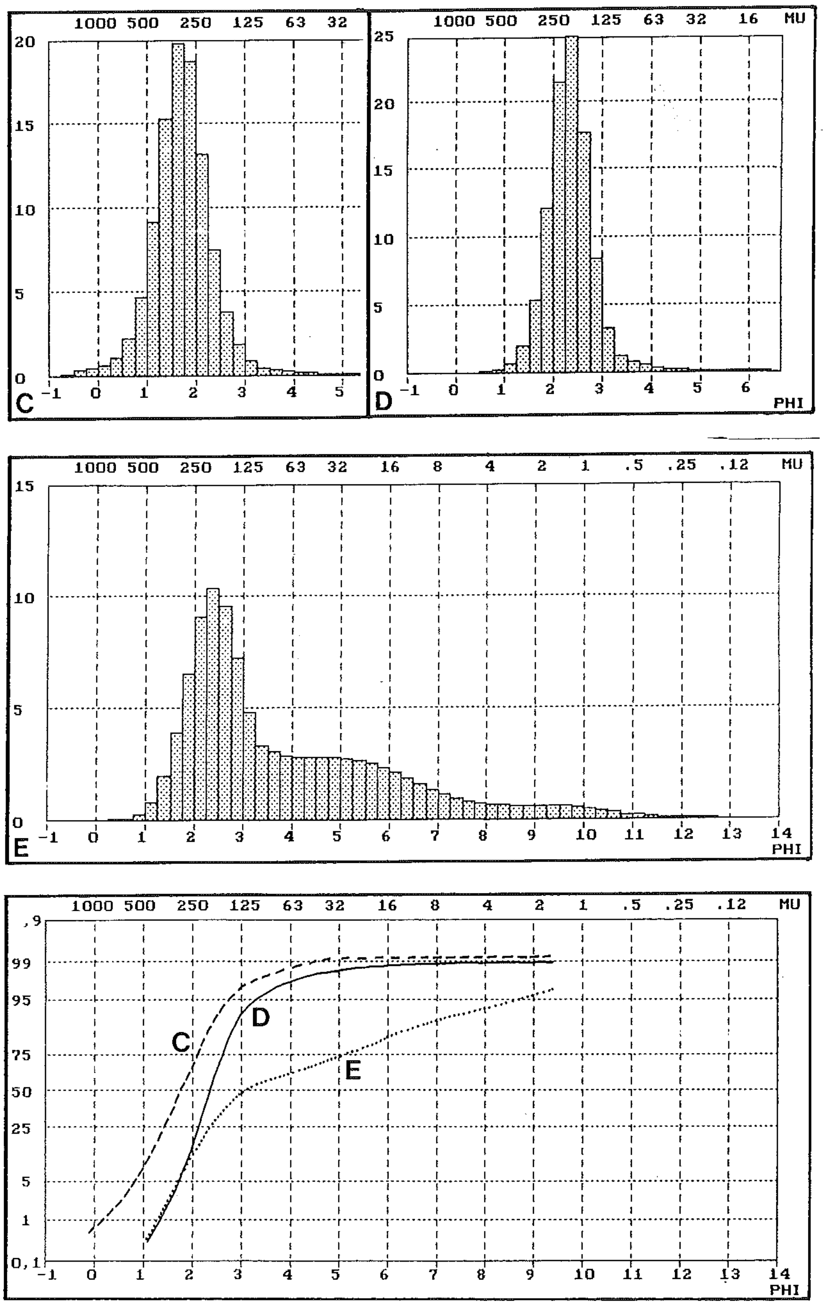


Figure 10
Grain-size histograms and cumulative curves of the channel deposits
(C: bedload; D: coarse infill; E: fine infill).

abrupt grain-size changes indicate abrupt changes in current velocity during the formation of both the channel subunits. During high current velocities sand was transported. During falling and low water stages, current velocity reduced very quickly, resulting in fine sand and humic silt deposition from suspension. This alternating depositional process is well illustrated in `Figure 9 (photo A and B). The relatively coarser grained sand beds (photo A) are dominated by horizontal lamination and low-angle cross-bedding. These bedding types indicate high current velocities in the channel. The depositional conditions may have resembled recent (semi-arid) analogues with high peak discharges (McKee et al., 1967) where the sand deposits are dominated by parallel lamination as well.

The silty beds are characterized by small-scale current ripple cross-lamination and massive bedding (Figure 9: photo A) pointing to lower flow regime and standing water conditions. Current direction in photo A is in general to the right, this is to the north, which is in agreement with the northwest trend of the channel. However, a few fine sandy intervals in the lower part of the lacquer peel (Figure 9: photo A) reveal a current direction to the left (=south). It is possible that during the falling water and low water stage the current was strongly deflected by local topographical elements (bars, scour pools) in the channel system. In that case, the opposed directions should be interpreted as falling stage modifications of the channel bed, as described by Collinson (1970). The finegrained nature of the beds, indicating a decreased current velocity, gives additional support for this interpretation.

The presence of well-developed climbing ripple cross-lamination in the fine-grained, silty layers is also indicative for a periodic rapid decrease in current velocity, in combination with a high suspension load (Figure 9: photo C). Note that the base of the fine-grained bed shows a rapid, but gradual transition from high current velocity deposition (sand) to low current velocity deposition of silty, humic fine sand in climbing ripples. The top of the fine-grained bed was clearly eroded in the following phase of high current velocity in the channel.

Grain-size characteristics of the channel sediments

The channel sediments (unit j: 9 samples) show quite variegated granulometric compositions (Figure 10):

i. The coarsest sediments (modal value 260 to 310µm; >98% sand fraction) are found at the base of the channel. They are characterized by a slight but clear '-coarse tail' representing the rolling bedload of the channel (Figure 10: histogram C, curve C).
ii. A second group contains samples which are only slightly finer (modal value 205 to 240µm; >96% sand fraction). However, a coarse tail is absent (Figure 10: histogram D, curve D). They are interpreted as coarse channel fill deposited during high water stage flow.
iii. The finest sediment is a mixture of very fine sand and silt (54% silt fraction) (Figure 10: histogram E, curve E). It may be interpreted as resulting from the settlement of suspension during the low water stage in the channel. The relatively low clay content (5%) is surprising taking into account the availability of clay in the till subsoil. It means that deposition did not take place in completely standing water.
iv. Other samples have mixed grain-size characteristics. They are clearly bimodal (180µm and 37µm) and contain large amounts of silt (30 to 35%) and very fine-sand. The clay percentage is low (<4%). They represent an alternation of fine and coarse channel fill. One sample from a cross-laminated set shows an intermediate grain size (modal value: 140 µm; 14,6% silt fraction) and is rather well sorted.

Palaeobotany and climate during the 43-35 ka BP period

Methods

The samples were prepared according to the methods described by Faegri & Iversen (1975) using a heavy liquid separation to remove the clastic component. A 40% HF (cold) treatment was added to remove the residual clay particles. The samples were embedded in glycerine-gelly and sealed with paraffin wax. A Zeiss light microscope with phase-contrast and a routine magnification of 630 was used during the analyses.

The percentage diagrams are constructed using a pollensum based on trees (*Pinus, Betula*), shrubs (*Salix, Betula nana, Populus, Juniperus*), Ericaceae, *Empetrum* and all terrestrial herbs including Gramineae and Cyperaceae. Other tree pollen in these cold-climate Middle Pleniglacial deposits have been regarded as secondary.

Palaeobotanical records of sediment unit d

Pollendiagrams GrW-d1, GrW-d2 and GrW-d3 (Figure 11).
Lithology: humic to peaty silt with *Carex rostrata* achenes.
Age: c. 43,3 ka BP (Figure 3 and Table 1).

The lowermost organic (peaty) silt was sampled at three different points. Due to a phase of cryoturbation little can be concluded as to the original position of the samples involved. Diagram GrW-d1 represents the most peaty sequence of the three. Reworking seems to have been limited (e.g. low *Alnus* values) and a relatively high percentage of locally produced Cyperaceae (according to the achenes predominantly *Carex rostrata*) is present. The relative contribution of the algae *Botryococcus* and *Pediastrum* is low. The combination of semi-terrestrial and shallow open-water indicators seems to indicate the presence of a hummocky mire, intermingled with shallow (seasonal) pools. This mire developed after a phase of fluvial activity and was probably promoted by impeded drainage due to the frozen subsoil. The diagrams GrW-d2 and d3 contain higher values for both algal spores and reworked pollen and seem to represent the pool facies of a mire. Their lithology is described as a slightly organic silt. The relatively high arboreal pollen in GrW-d2 and d3 (c. 40%) in comparison to GrW-d1 (c. 10%) is either a result of admixture of reworked *Pinus* and *Betula* pollen or can be ascribed to a suppression of the AP values in GrW-d1 due to the over-representation by the local Cyperaceae.

The aquatic (*Myriophyllum alterniflorum, Myriophyllum spicatum*) and riparian vegetation (*Lycopodium selago, Selaginella selginoides*) indicate continuous pioneer conditions. These conditions can possibly be ascribed to repeated inundations by a then active river system and deposition of silt from sediment load. The limited input of sediment permits the vegetation to persist, both in the pools and on the hummocks. This would explain the absence of a hydroseral succession in the three sections dealt with. Among the shrubs *Betula nana, Salix* spp. and, although in low frequencies, *Populus cf. tremula* and *Juniperus* need to be mentioned. The low frequencies of *Juniperus* and its discontinuous occurrence do not permit any conclusions with respect to the prevailing temperature at that time. The vegetation as described can best be compared with a low arctic tundra.

A characteristic of this unit d is the occurrence of chinophilous species like *Dryas octopetala* and *Gentiana nivalis*. A long-lasting snow cover and a relatively short growing season may have been the main characteristics of this environment. Indicators for disturbed ground and bare mineral soils (Cruciferae, *Artemisia*) related to frost pene-

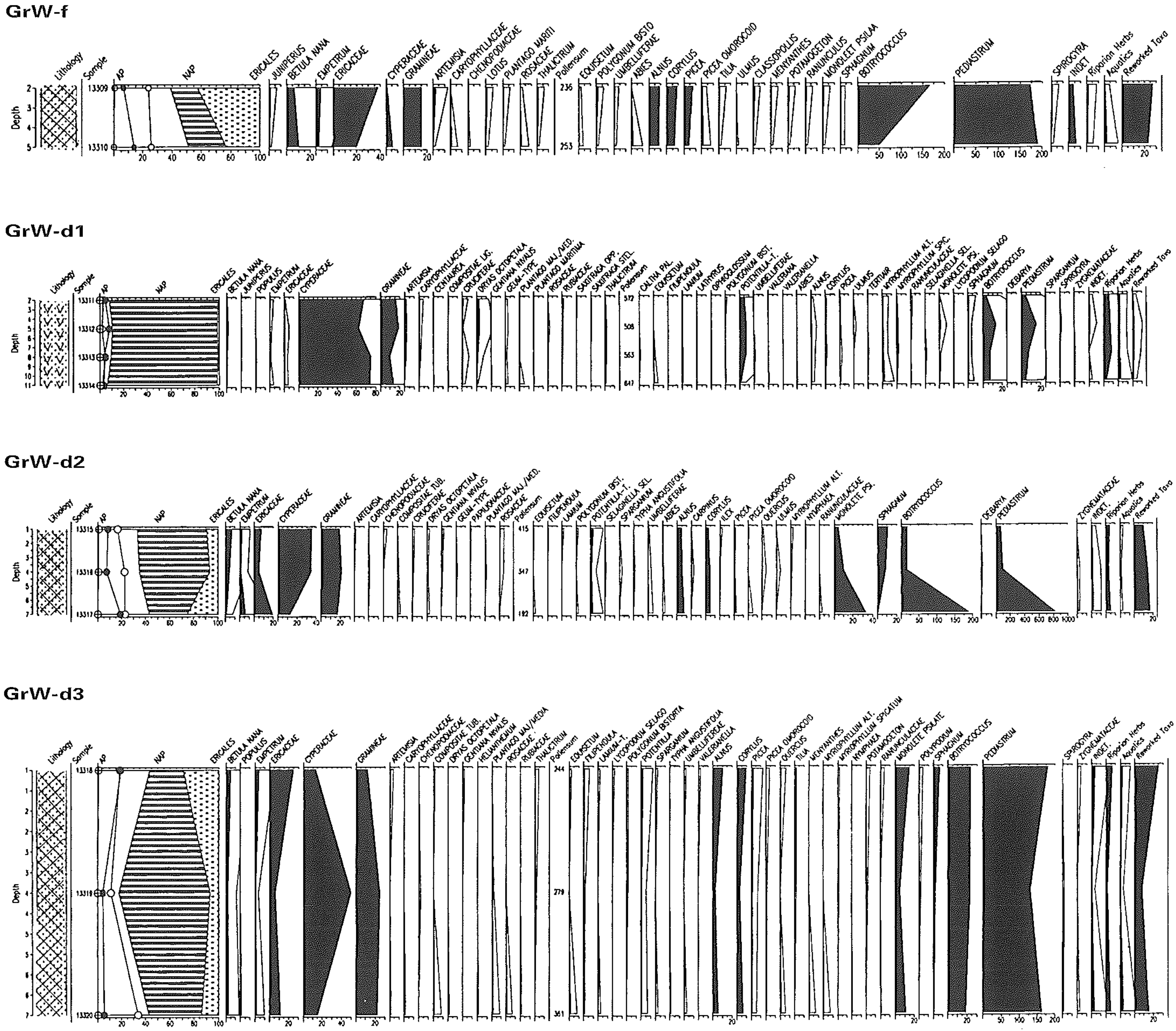


Figure 11
Pollen diagrams of Grouw, lithologic units d and f

tration and fluvial or aeolian erosion are virtually absent. It is assumed that the presence of a snow cover exerts a mild influence on plant life.

Palaeobotanical record of sediment unit f

Pollendiagram GrW-f (Figure 11).
Lithology: humic silt.
Age: c. 38,7 ka BP (Figure 3 and Table 1).

The two spectra account of some important changes in the palaeoenvironment between the period of deposition of the lower peaty silt layer unit d, and the silt of unit f. GrW-f represents an open water facies dominated by algal spores (*Pediastrum* and *Botryococcus*) and with some reworked pollen of Eemian and early Weichselian age (e.g. *Picea omorocoides*). A major contrast is the absence of *Myriophyllum species* and the relatively higher values for *Artemisia*. Moreover, in the vegetation bordering on open water, *Dryas octopetala* and *Gentiana nivalis* are lacking. Possibly, in the absence of a long-lasting snow cover, frost penetration became more general and promoted the spread of bare mineral soils. Consequently erosion and deposition processes became relatively more important and silt and sand would have been trapped in the shallow lakes represented by unit f. These conditions in return would have expelled clear water depending species such as *Myriophyllum alterniflorum*. The minor role of a snow cover had a positive influence on the spread of *Betula nana* in the vegetation.

Palaeobotanical record of sediment unit h

Pollendiagram GrW-h (Figure 12).
Lithology: silty fine-detrital gyttja with thin sand lenses.
Age: c. 37,8-36,9 ka BP (Figure 3 and Table 1).

Pollenrecord GrW-h derives from a highly organic lacustrine deposit with faint horizontal sand laminae. This type of sediment proved to be unique for the exposure at Grouw. Macroremain analyses of unit h demonstrated the presence of *Myriophyllum spicatum* seeds, *Batrachium* fruits and a small fraction of *Menyanthes* seeds. Throughout the profile the AP values remain fairly low (c. 20%) while the herb assemblage is dominated by grasses and sedges intermingled with *Potentilla* (possibly *P. palustris*) and *Dryas octopetala*. The combination of taxa points to a low arctic tundra.

Zone GrW-h1 (72-59 cm)

The presence of a continuous *Juniperus* curve (c. 1%) right from the base is remarkable. Its values are relatively low but nevertheless, in the climatic conditions envisaged, the *Juniperus* shrubs may have remained rather stunted and their height will not have outranged the thickness of the snow cover (Chernov, 1980). Consequently, in these stunted forms pollen dispersal will have been limited. The juniper in this case is interpreted as a sign for a slight climatic amelioration, with summer temperatures rising from around 10°C to 11-12°C (Kolstrup, 1980). *Juniperus* occupies a zone between the woody shrub tundra and the boreal birch forest. Tree birch does not react in the pollen record. Instead *Betula nana*, an element of the woody shrub tundra, declines at the end of zone h1. When discussing the climate of the Middle Weichselian many alternative explanations have been proposed to clarify the virtual absence of trees (e.g. Kolstrup & Wijmstra, 1977; Brinkkemper et al., 1987; Kolstrup, 1990; Ran, 1990) although for some time intervals the mean July temperature seems to have reached values permitting the timberline to shift northwards.
The climatic improvement in the basal part of the sequence is supported by the local presence of leaf-hairs of *Ceratophyllum demersum*, a species that requires a mean summer temperature of c. 13°C (Van Geel et al., 1981). A gradual increase in water depth seems to be reflected in the local vegetational succession. The initial phase is dominated by *Menyanthes, Potentilla* and *Equisetum* indicating the presence of a mire with (seasonal) shallow pools.

Zone GrW-h2 (59-17 cm)

Subsequently water depth increased as indicated by the increase in Ranunculaceae subgenus *Batrachium, Potamogeton* and *Myriophyllum* species. The sum of the aquatics increased consequently. Standing open water developed with *Pediastrum* as the most dominant algae. It is important to observe that this increase in water depth is not matched by an increase in reworked pollen and hence cannot be ascribed to increased floodings by the adjacent river and a concomitant development of levees.
The lacustrine sediments at Grouw reflect a stable episode with rather low environmental dynamics in contrast to the overlying and underlying sandy crevasse sediments which represent a highly dynamic fluvial environment (see also sedimentary environments units g, i and j). According to Kolstrup (1990) a high environmental dynamics (e.g. by high wind velocity) is one of the arguments to explain the absence of trees during the Middle Pleniglacial. It may be doubted, however, whether strong wind action, at least during the growing season, should be an argument to explain the absence of treebirches during the Middle Pleniglacial. The lacustrine sediments of unit h, like in other cases (Zagwijn, 1974, diagram Hengelo K.N.Z.; Ran et al., 1990; Van Huissteden, 1990), are rather evenly laminated and do not show signs of wave ripples.
In the central part of zone h2 the lake seems to reach its maximal depth. Here even one *Nuphar* pollengrain is registered. Towards the top of zone h2 both *Juniperus* and *Empetrum* decline. For both species a protecting snow cover during the severe winter period is indispensable (Iversen, 1954; Van der Hammen, 1951). Their simultaneous decline indicates the decreasing role of this winter snow cover.

Zone GrW-h3 (17-0 cm)

Betula nana spreads again indicating a subtle shift towards the pure shrub tundra although *Salix* remains low. This can also be attributed to the diminished role of the snow cover. Instead Caryophyllaceae, Cruciferae, Compositae and Convolvulaceae increase. These taxa are indicative of open ground conditions and the break-up of a continuous vegetation cover (Lowe & Walker, 1977; Pennington, 1977). In the absence of a protecting snow cover not only *Empetrum* and *Juniperus* disappear but these conditions also permit frost disturbances to occur more easily, creating in this way open ground conditions. Another effect of the diminished snow cover during winter is the decline in effective precipitation. This is confirmed by the rapid hydroseral succession registered in the top, where the sum of the aquatics declines (especially *Myriophyllum* spp.) and among the upland herbs *Artemisia, Thalictrum* and Chenopodiaceae spread, which may be interpreted as an indication for somewhat drier conditions. A similar succession is registered in the thawlake sediments of the Hengelo basin (Ran et al., 1990, zone HGA-3a and 3b). Here even *Ephedra distachia*-type forms a constituent of the vegetation surrounding the lake.

Locally, the shallow pool became colonized by *Polygonum bistorta, Caltha palustris*, grasses, *Valeriana*, pleurocarpe mosses and algae (*Pediastrum, Spirogyra*). Both *Filipendula* and *Menyanthes* are expected to take part in this hydroseral succession. Their absence may be interpreted as a sign for decreasing summer temperatures. *Filipendula* thrives at mean summer temperatures around 10°C while *Menyanthes* has a lower limit of 8°C (Kolstrup, 1980). *Polygonum bistorta* has a much lower limit (5°C) and its increase in the top could possibly be explained by the absence of a competitor like

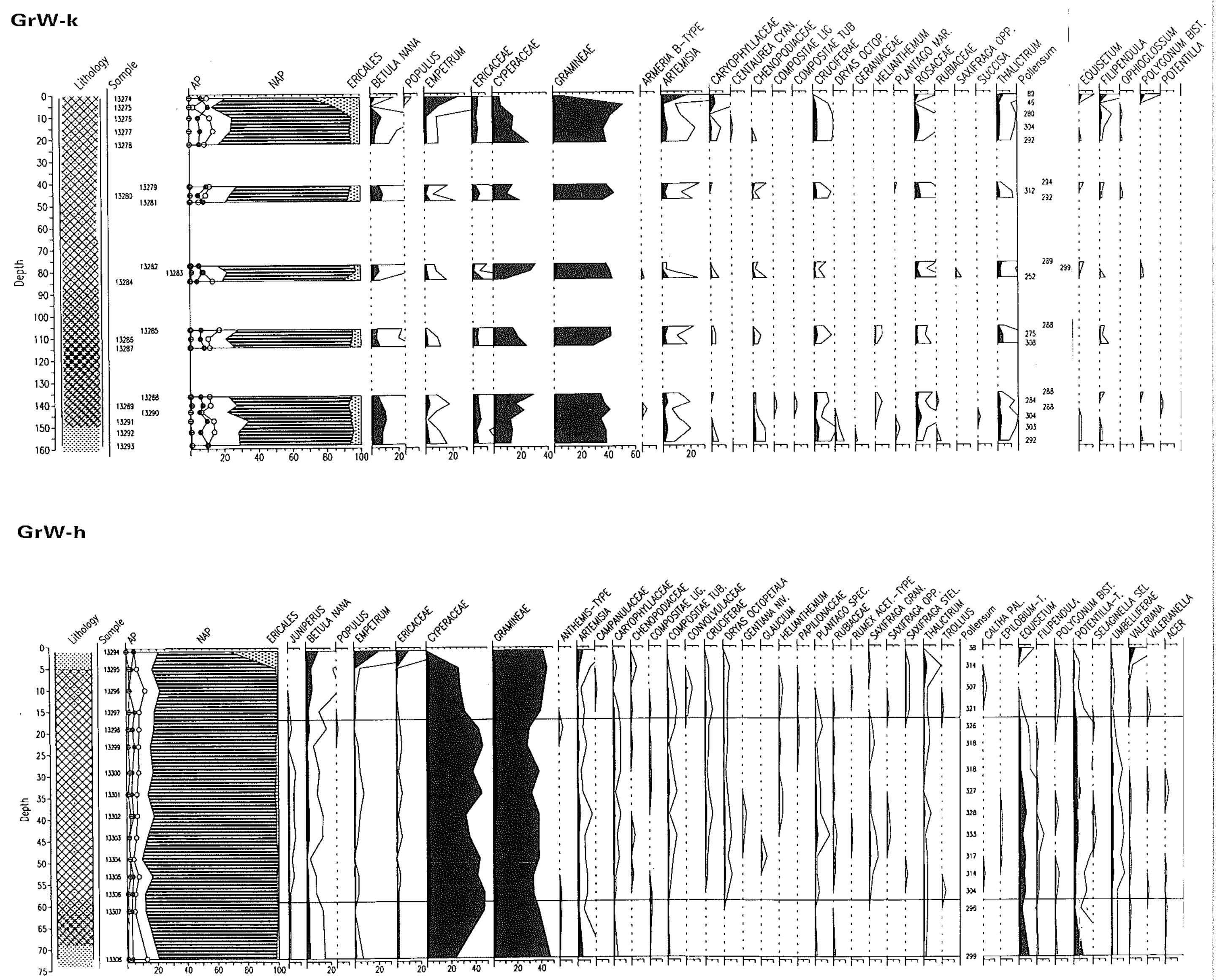


Figure 12
Pollen diagrams of Grouw, lithologic units h and k.

Menyanthes. Besides indications for more prominent dry conditions, the botanical record provides indications for a mean summer temperature lower than 8°C.

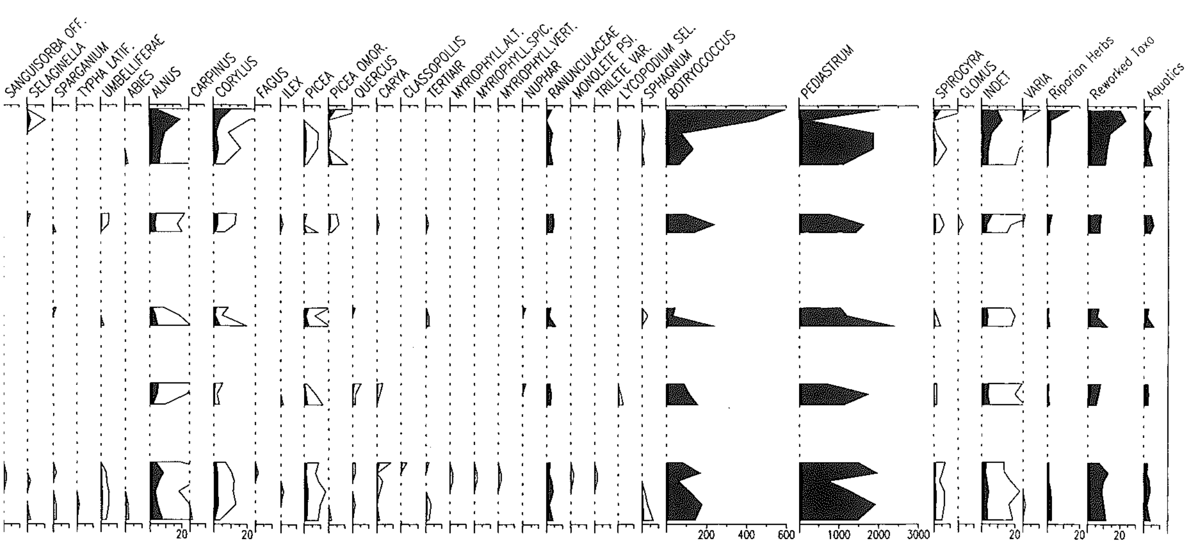
Palaeobotanical record of sediment unit j

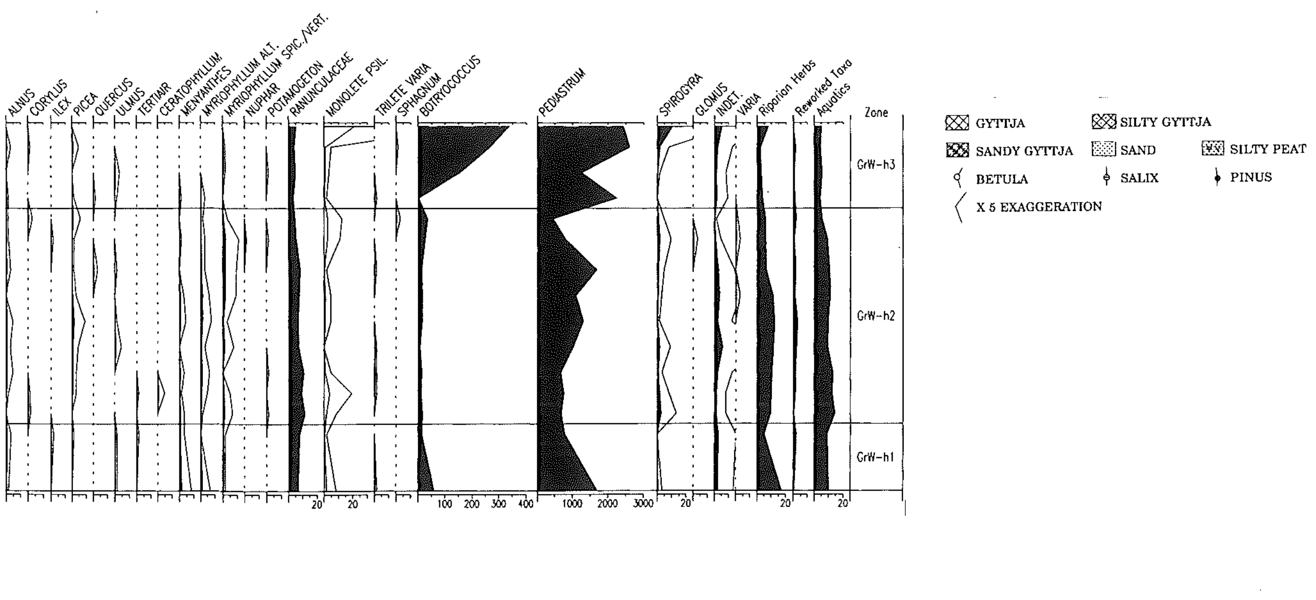
No pollendata are available from the organic silts in channel unit j. Pollenanalyses on these sediments seemed inappropriate because of the erosional character of the channels. Wood, reworked from the underlying Eemian peat has been noticed during the field examinations. Some interpretations towards the palaeoenvironment can still be made, based on a carefully examined sample which was taken close to the ^{14}C-sample of 36,2 ka BP (table 1: sample 8; RGD, 1991b). This sample revealed a rich flora of *Salix* leaves (*S. herbacea, S. reticulata* and *S. myrsinites*) and occasional findings of *Dryas octopetala* leaves. These leaves are trapped in pleurocarpe moss layers that penetrated the pools which were left after a flood phase. Other species encountered in these sediments are *Carex rostrata, Potamogeton filiformis* and *P. natans*.

This palaeobotanical assemblage seems to fit the registered change towards a vegetation dominated by a prolonged snow cover (shortly after 36,9 ka BP), traceable in the uppermost spectrum of zone GrW-h3. The high effective precipitation, possibly combined with a decline in water storage capacity resulting from permafrost, seems to have been responsible for the return of the fluvial dynamics. High fluvial dynamics and in particular the increase in peakedness are responsible for the deposition of crevasse splay unit i.

Palaeobotanical record of unit k

Pollendiagram GrW-k (Figure 12).





Lithology: humic sand grading upwards into a humic silty clay. Age: c. 35,5-35,4 ka BP (Figure 3 and Table 1).

The floristic diversity in sequence GrW-k is considerably less than in sequence GrW-h. Throughout this zone clastic deposition in the abandoned gully is present and is stressed by the relatively high presence of reworked pollen (c. 15%). The low relative values for the aquatics (Ranunculaceae subgenus *Batrachium, Myriophyllum* spp.) indicate less favorable conditions than during the deposition of unit h (zones GrW-h1 and h2). *Pediastrum* confirms the presence of predominantly standing water. *Empetrum* and *Betula nana* are amongst the most dominant woody shrubs. *Juniperus* is absent from the pollen record. *Filipendula* is continuously present and indicates mean July temperatures of around 10°C (Kolstrup, 1980). Open ground indicators (Caryophyllaceae, Compositae, Cruciferae) are present throughout the profile and particularly so in the upper part of the infill, where these taxa increase and *Centaurea cyanus* is present (Iversen, 1954). *Potentilla* (possibly *P. palustris*) is taken as an indicator for waterlogged conditions around the site (Ran, 1990).
The palaeobotanical record provides a picture of a woody shrub tundra intermingled with patches of open ground and waterlogged wet meadows. The palaeobotanical evidence from GrW-k indicates a mean summer temperature around 10°C. According to Iversen (1954, 1973), Kolstrup (1980) and Brinkkemper et al. (1987) the presence of *Armeria* B-type pollen indicates that the mean January temperature did not decline below -8°C. Ran (1990) strongly doubts the usefulness of *Armeria* for climatic reconstruction. Also the presence of periglacial structures immediately below and above unit k argues against higher winter temperatures.

Chronology of the Pleniglacial deposits

The occurrence of several organic layers in the Grouw exposures allows the establishment of a detailed chronology by ten ^{14}C-dates. Table 1 gives a list of the ^{14}C-dates, the material which has been dated, the lithological unit and $\partial^{13}C$. Two additional dates, of samples taken by the Geological Survey of the Netherlands have been included (RGD, 1991a, 1991b). The residue and extract of most samples have been dated, because contamination by younger humic acids can strongly influence samples in the 43-35 ka BP time range. In Figure 3 only the residue dates are presented.
In general, the dates show a rather consistent succession from 43 ka BP at the base to 35 ka BP at the top, covering an at least 8000 ^{14}C-years interval of the Weichselian Pleniglacial. For most samples the residue and extract dates are in fairly close agreement with each other (table 1). This means that contamination by younger humic acids is absent and the dates must be regarded as reliable. Some dates, however, especially those from the channel infilling (subunit j1, base unit k) do not correspond with their lithostratigraphic position (see Table 1 and Figure 3). Two major error sources may account for the deviating datings: 1. contamination by humic acids. 2. contamination by reworking of older organic matter.

Contamination by humic acids

The reason for the high extract age of unit d (Table 1: date 12) is unclear. Possibly humic acids from the underlying Eemian peat have infiltrated by groundwater flow. The two residue dates are in good agreement. Because the dated material consists of a (semi)terrestrial silty peat with large amounts of *Carex rostrata* seeds in the macroremains, these residue dates (42,7 and 43,9 ka BP) of unit d (sample 12) are regarded to be reliable.
The large deviation between the residue and extract date of sample 1 (not included in Figure 3), taken from the top of unit k (Table 1; RGD, 1991a), is most likely due to contamination by younger humic acids in the extract date. The podzolisation process in unit l during the Holocene will have led to the transport and precipitation of humic acids in and on top of the less permeable silt unit k.

Contamination by reworking of older organic matter

The two dates taken from the channel subunit j1 (Figure 3; Table 1: nr. 6 and 7) are problematic. Residue and extract dates show large differences. The samples have been derived from sandy, humic silt beds, occurring in between fluvial sand beds. The humic silt beds are interpreted as deposits of a waning flow at the end of a snow melt event. The presence of (climbing) ripple lamination clearly points to a water-laid origin of the silts and the organic material in the silt beds is therefore definitely reworked. Screening of the samples under the binocular did not reveal any major indications for reworking of the underlying Eemian peat. For this reason, the samples were thought to contain autochthonous organic material only (e.g. moss leaves) which was transported over a short distance in the channel. The stratigraphic position of subunit j1 (Figure 3) shows that unit j1 is time equivalent with unit g, dating between 38,7 and 37,8 ka BP. However, the age of samples 6 and 7 from subunit j1 are 40,9 and 42,7 ka BP. Therefore, it must be concluded that these channel samples do contain some reworked organic material and the residue ages are too old.
Sample 4, from the base of unit k (38,4 ka BP), represents the start of the fine-grained, lacustrine infilling of channel j2. The dated material consists of a calcareous, sandy, coarse-detrital humic silt. The calcareous nature of the sediment and of the depositional environment may in theory be responsible for the aging of the sample due to the uptake of old carbon in the assimilation process of plants (hard-water effect). However, the $\partial^{13}C$-value of the

sample is comparable with the values of the non-calcareous samples. In agreement with the findings of Van Huissteden (1990) for the Middle Pleniglacial deposits in the Dinkel valley, it is concluded that the ass,imilation of older carbon cannot be held responsible for the apparently too old date. The CO_2 in the lake environment of unit k seems to have been in equilibrium with the atmosphere, perhaps because of the shallow nature of the water body. Sample 4 contains a high amount of clastic material pointing to current deposition. The deviating residue age of the base of unit k (sample 4) is most likely to be explained by fluvial reworking of older organic material. This is supported by the palaeobotanical data (pollen diagram Grouw, unit k) in which the presence of *Alnus, Corylus* and other thermophilous trees points to the reworking of underlying Eemian deposits.

Sample 8 (not included in Figure 3) was taken 2,25 m above the base of unit j in the north exposure by the Geological Survey of the Netherlands (table 1; RGD, 1991b). The dated material consists of a 4 cm thick, pure moss peat, found in the channel sequence. The nature of the material makes it highly suitable for ^{14}C-dating and the date (36,2 ka BP) has therefore to be regarded as reliable. Unlike the other ^{14}C-samples, this sample was taken from the exposure north of the Prinses Margriet canal. The stratigraphic position of sample 8 is not exactly known, because within channel unit j large-scale unconformities have been found, separating different phases of channel activity and infilling. The boundary between the subunits j1 and j2 in the southern pit showed a very gentle dip to the north. It is therefore likely that sample 8 in the nort-

Table 1
^{14}C-dates from the Pleniglacial sequence at Grouw (southern exposure, except date 8 taken from the northern exposure).

N	Unit	Field code	Material	^{14}C date (BP) R=residue, c=coarse, f=fine E=extract	Labo. number	$^{13}\delta$ °/..	Comments
1	(k)	Grouw GMIV/1 (RGD)	gyttja	R=36,370+370-350 E=26,850±140	GrN-18339 GrN-18637	- -	humus infiltration
2	k	Grouw IX-top	humic silt/gyttja	Rf=35,350+550-500 Ef=34,900+650-600	GrN-16194 GrN-16195	-27,63 -26,23	reliable
3	k	Grouw VII-top	humic silt/gyttja	Rc=35,200+650-600 Rf=35,800+700-650 Ecf=35,300+1000-900	GrN-16196 GrN-18451 GrN-18450	-28,22 -26,37 -26,85	reliable reliable
4	k	Grouw V-mid	sandy, humic silt	Rf=38,350+1000-900	GrN-16197	-27,31	calcareous material/ reworking
5	j2	Grouw 4.2	sandy, humic silt	R=35,910+340-330 E=33,900+500-400	GrN-16232 GrN-16233	- -	reliable
6	j1	Grouw 2.2	sandy, humic silt	R=40,850+600-550 E=35,150+600-550	GrN-16231 GrN-18636	- -	reworking
7	j1	Grouw 0.1	sandy, humic silt	R=42,650+800-700 E=39.900+650-600	GrN-16229 GrN-16230	- -	reworking
8	j2	Grouw GMNI/2 (RGD)	moss peat	R=36,180+340-330	GrN-18336	-	reliable
9	h	Grouw I(14-20)	gyttja	Rf=36,850+800-750 Ef=35,350±600	GrN-16199 GrN-18449	-27,25 -27,67	reliable
10	h	Grouw II(27-34)	gyttja	Rf=37,750+900-800 Ef=38,800+1000-900	GrN-16200 GrN-16201	-26,26 -27,62	reliable
11	f	Grouw III	silt	Rf=38,700+1100-1000 Ef=36,800+1400-1200	GrN-16202 GrN-16203	-27,35 -25,58	reliable
12	d	Grouw IV	peaty silt	Rc=43,900+1500-1300 Rf=42,700+1300-1100 Ecf=51,000+4500-2900	GrN-16204 GrN-18452 GrN-16205	-29,27 -28,93 -27,53	reliable reliable ?

hern pit, although at almost the same topographic level as samples 6 and 7 (subunit j1), is younger, because it is situated in a higher stratigraphic position (subunit j2).

Age of the periglacial levels in the Pleniglacial sequence

The Weichselian Pleniglacial sequence is characterized by several levels of ice-wedge casts each associated with cryoturbations. Seven cycles of permafrost development and degradation have been distinguished (Figure 3) (Vandenberghe & Kasse, 1993). Especially the channel overbank facies (Figure 3: units c-i) and top units k and l are heavily deformed by periglacial activity (Figure 4: photo A and B). Channel unit j is only weakly disturbed, although locally cryoturbated levels and frost cracks have been found within the channel sequence, illustrating its stacked character.
The presence of several organic units enables accurate dating of the periglacial levels (Tables 1 and 2). The oldest periglacial level (1) consists of ice-wedge casts, which penetrate the Eemian peat unit b (Figure 4: photo C). They are overlain by an erosional surface (pebble layer) followed by the units c and d ending at c. 43,3 ka BP. This pebble layer may be correlated with the late Early Pleniglacial pebble horizon in the southern Netherlands (Vandenberghe, 1985). Therefore, periglacial level 1 dates between 43,3 ka BP and the Eemian and is probably of Early Pleniglacial age.
The levels 2 and 3 date between 38,7-43,3 ka BP and 37,8-38,7 ka BP respectively (Table 2). In general, the development of permafrost may have started already during the end of a sedimentation cycle (c-d, e-f), due to decreasing sedimentation rates and flooding frequency. So, the permafrost development of cycle 2 could begin during the formation of the fine-grained unit d, this is around 43,3 ka BP. However, permafrost degradation and formation of the involutions certainly occurred later than 43,3 ka BP, since unit d is affected by the involution process. The same holds true for cycle 3, where permafrost development could start around 38,7 ka BP and permafrost degradation occurred later than 38,7 ka BP, but before 37,8 ka BP, being the date of the overlying gyttja layer h (table 2). Periglacial level 4b affects the top of unit h and is therefore younger than 36,9 ka BP. It is overlain by unit k which dates from 35,5 ka BP.
Like the start of the cycles 2 and 3, the permafrost development of cycle 5 may have started already in the last stage of sedimentation of fine-grained unit k, this is around 35,4 ka BP. The time of degradation of the permafrost of level 5 and the overlying levels 6 and 7 is poorly known. Upper Pleniglacial sediments (Beuningen Gravel Bed, Older Coversand II) are missing because of erosion or non-deposition, so it must be assumed that levels 6 and 7 are older than the Beuningen Gravel Bed (c. 18 ka BP). The large ice-wedge casts of level 7 form, together with the casts from the underlying level 6, classical examples of syngenetic ice-wedge casts. They may have been formed shortly after 35 ka BP, but it is also possible that they developed during the last glacial maximum.

Lithological unit	Permafrost development	Permafrost degradation	Radiocarbon age (ka BP)
m			Holocene
soil formation/ hiatus			Early Holocene/ Late Glacial/ Late Pleniglacial
	7	7	18 - 35,4
	6	6	< 35,4
l			< 35,4
	5	5	≤ 35,4
k	(5)		35,4 - 35,5
j			35,5 - (36,2)38,7
i			35,5 - 36,9
	4b	4b	35,5 - 36,9
h			36,9 - 37,8
	4a	4a	37,8 - 38,7
g			37,8 - 38,7
	3	3	37,8 - 38,7
f	(3)		38,7
e			38,7 - 43,3
	2	2	38,7 - 43,3
d	(2)		43,3
c			> 43,3
Discordancy			late Early Pleniglacial
	1	1	43,3 - Eemian
b			Eemian

Table 2
Ages of the lithological units and the periglacial levels in the Pleniglacial sequence at Grouw.

Genesis of the periglacial and sedimentary cyclicity

The overbank facies (units c,d,e,f,g,h,i,k,l) reveal a strong sedimentary and periglacial cyclicity. The sediment cycles consist of stacked, fining-upward sequences from medium or fine sand into humic silt or gyttja (c-d, e-f, g-h, i-k). Erosion at the base of a new cycle seems to have been of minor importance.
The periglacial levels are found in close relation with the sedimentary cycles. The topographic surface at the time of permafrost development probably coincided with the top of a fining-upward sequence. During the final phase of a sedimentation cycle the accumulation rate and flooding frequency decreased and permafrost re-established and ice wedges formed in the overbank environment. However, the tops of the cryoturbated zones (this is the moment of permafrost degradation) do not correspond completely with the tops of the fining-up sequences. The cryoturbations often also affect the base of the overlying sand unit. This indicates that permafrost degradation occurred at the start of a new overbank sedimentation phase. Because of the renewed flooding, the top of the permafrost thawed and the fine-grained sediments became oversaturated. These oversaturated sediments of

the previous sedimentation cycle, together with the sand of the new sedimentation cycle, involuted in the form of cryoturbations.

These twofold cycles, consisting of a sedimentary cycle followed by a periglacial cycle, have been recognized at least four times (units c-d, periglacial level 2; units e-f, level 3; units g-h, level 4; units i-k, level 5). The sedimentary cycles and their corresponding periglacial levels 3 and 4 can be dated rather accurately. They lasted less than 5,5 and 3,2 ka respectively.

Two trigger mechanisms for this sedimentary and associated periglacial cyclicity are discussed: i. cyclicity due to intrinsic changes in the fluvial system (internal factors) or ii. cyclicity caused by climatic changes leading to floodplain adjustment (external factors).

Cyclicity by intrinsic changes

In a generally aggradational river system, when sediment supply exceeds transport capacity, changes in the channel course by avulsion or lateral migration may lead to a vertical succession of coarse-grained channel or crevasse splay units and fine-grained overbank units. Due to lateral channel migration coarse-grained sediments can subsequently be topped by fine-grained, vertical accretion deposits or overbank sediments. Unfortunately, channel facies of the overbank units c, d, e, f, k and l have not been preserved, so the position of the channel at that time is unknown. However, the coarse-grained crevasse splay and fine-grained backswamp units are arranged in normal fluvial fining-upward sequences which can be explained by lateral channel migration and aggradation. This mechanism, being sedimentologically the most simple one, is proposed by Vandenberghe & Kasse (1993). Such intrinsic fluvial changes can explain the major part of the sedimentary sequence at Grouw, except for unit h.

Cyclicity by climate change

The intrinsic changes, mentioned above, cannot explain the middle part of the overbank sequence (Figure 3: unit h). During the deposition of the sandy overbank units g and i, the channel is obviously nearby (Figure 3: subunits j1 and j2). In gyttja layer h, the increase of the sand - content and number of sand laminae in the direction of the channel margin indicates that the channel was nearby as well. The presence of a lake environment (unit h) close to the channel indicates that flooding of the overbank environment had decreased in comparison with the previous and later periods. Instead, only incidental floodings occurred as represented by the thin sandy intercalations. The reason for this decrease in flooding can be a general decrease in discharge, decrease in discharge fluctuations or by a small incision of the river channel. Incision and changes in discharge can be attributed to climatic changes (Bohncke & Vandenberghe, 1991 and references cited there). Positive arguments in favor of a distinct temperature rise have been derived from the palaeobotanical record. The continuous curve of Juniperus points to a temperature rise of 2°C. The highly organic nature of unit h also suggests a higher organic productivity in this time interval. Therefore, the vertical succession of units g, h and i suggests an external factor (i.e. climate) governing the depositional environment.

Climatic development and thermokarst lake formation during the Weichselian Middle Pleniglacial

The results of the previous paragraphs have been summarized in Figure 13. The lithological units mostly date from the Weichselian Middle Pleniglacial. The coarser-grained overbank units, dominated by horizontal lamination, have been interpreted as shallow fluvial, crevasse splay deposits. The fine-grained, often massive, overbank units have been deposited in backswamp and lacustrine environments. Aeolian activity appeared to be of minor importance and was established only in the units c and possibly l, this is before 43,3 ka BP and later than 35,4 ka BP. The channel unit j is characterized by largescale cross-bedding, small-scale cross-lamination and climbing ripple lamination. The sedimentary structures reveal episodic discharges related to the snow melt period. The palaeovegetation, based on pollen and macro remains, was a fairly stable shrub tundra throughout the 43 - 35 ka BP period. Phases with a more chinophilous shrub tundra vegetation were established around 43,3 ka, between 37,8 and 36,9 ka and around 36 ka BP. Periglacial structures (ice-wedge casts, cryoturbations) were found in at least seven levels, which indicates that permafrost frequently developed and degraded in the investigated time span.

The climatological implications derived from the sedimentary sequence will be dealt with in the following paragraphs. Special attention will be given to unit h which was interpreted as a thermokarst lake deposit, formed by a short phase of climatic warming during the Hengelo Interstadial.

Climatic conditions derived from the channel sediments

The rapid and repetitive alternations of sand and silt in the channel sequence (unit j) are highly characteristic for this periglacial fluvial environment (see § episodic flow structures). The rapid grain-size variations have been explained by discharge related variations in current velocity. Such rapid discharge fluctuations point to a strongly peaked character of the floods. The repetitive character of the bedding is evidence for a frequently recurring process. The silt beds cannot be regarded as "normal" final stages of channel infilling, e.g. by the abandonment of the channel or by vertical accretion. This is clearly demonstrated by comparison of Figure 9, photo B (alternating sand-silt bedding) with photo D (fining-upward in abandoned channel). The silt beds occur within the channel sequence and are part of the active channel system. They formed during relatively brief intervals of low current velocity or standing water in the channel. Regarding the periglacial environment in which these deposits were formed, it is likely that this repetitive process was the annual snow melt water discharge. The existence of a prolonged snow cover during the formation of channel subunit j2, between 36,9 and 35,5 ka BP, is suggested by the presence of a chinophilous vegetation with *Salix* and *Dryas*. Such a snow cover accumulated outside, but also within the shallow channels of the frozen river floodplain because of the low winter temperatures.

Like in present-day periglacial rivers (Collinson, 1970) the snow cover will have melted quickly in late spring, feeding the channel with large amounts of snow melt water. The water level then rose, so that the corresponding overbank environment could be inundated also. In this high water stage sand was flushed through the system (Figure 10: curve C and D). As soon as the snow had disappeared, the discharge probably dropped to a very low level. In this respect, it has to be taken into account that the palaeo-Boorne river drained a small rain and snow-fed catchment. Furthermore, because of the presence of permafrost on the interfluves the groundwater recharge was limited and therefore also the intensity of groundwater flow and river base flow will have been low. So after a snow melt period the discharge dropped suddenly resulting in an abrupt decrease in stream power. Sandy silt was deposited at low current velocities in the low-gradient floodplain of the Boorne (approximately 25 cm/km for the top of the Pleistocene sediments; De Groot et al., 1987). It is even likely that standing water conditions occurred, e.g. in scour pools of the channel, in which silt deposited from suspension. In these shallow, low-energy environments at the margins of channels or in pools, plants could establish rapidly during the summer months. This idea is supported by the presence of laminae consisting of pleurocarpe mosses, which were found locally within the fine-grained beds in channel subunit j2 (Table 1: ^{14}C-date nr. 8 on moss peat). These mosses are capable of growing in open water, forming floating mats on the water surface. In the following winter season, the pools and their vegetation froze and were covered by snow. During the next spring thaw period, the remains of the vegetation were released and reworked by the flood water and deposited during the falling water stage as detrital material in a silty bed. The silty beds indeed do contain a lot of reworked plant remains (especially moss leaves) in the organic residue.

Chronology of thermokarst lakes in the Netherlands

In the Weichselian Pleniglacial sequence at Grouw several phases of thermokarst, reflected by cryoturbation levels, have been established. Apparently, only during one phase the ground subsidence by the thermokarst pro-

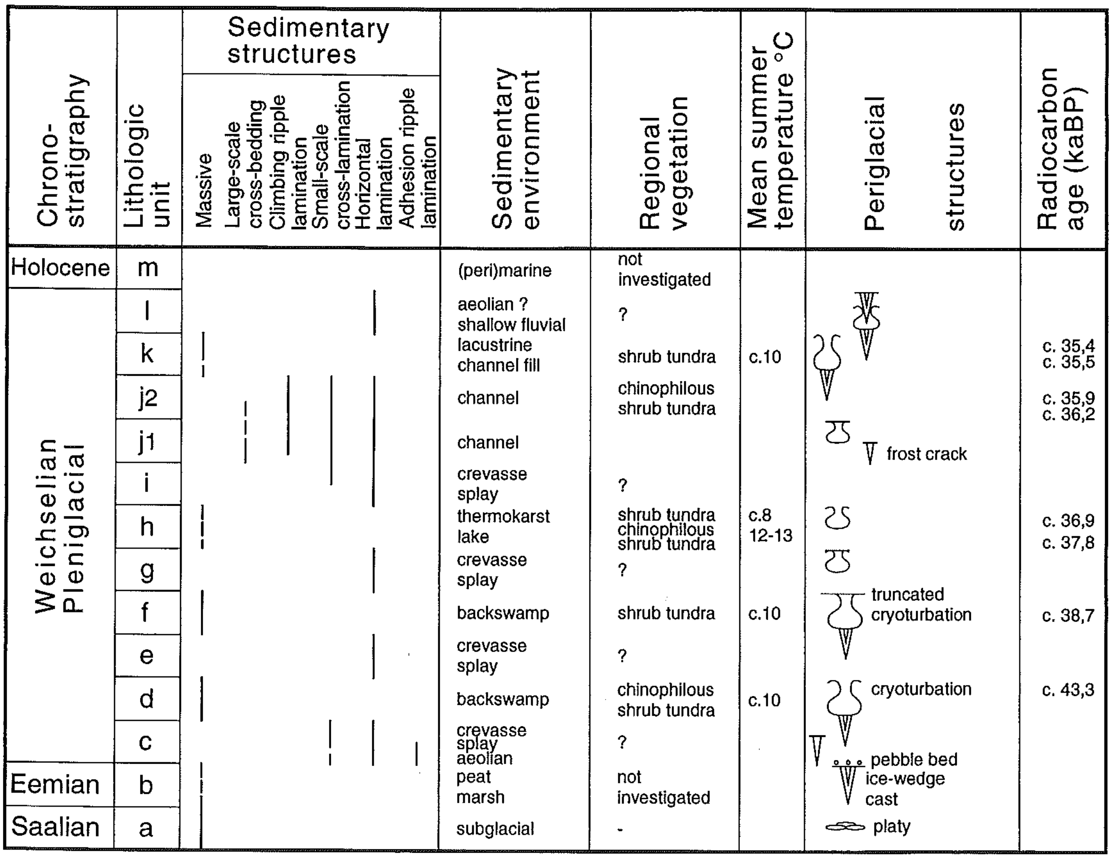


Figure 13
Range chart of sedimentary, palaeobotanical and periglacial characteristics of the Grouw exposure.

cess was so strong that a thaw lake formed. The age of the thaw-lake fill (unit h) is between 36,9 and 37,8 ka BP; thaw-lake development occurred between 38,7 and 37,8 ka BP. These dates are in close agreement with Van Huissteden (1990) and Ran et al. (1990), who proposed thaw-lake development in the Dinkel valley between 39,6 and 33,1 ka BP. The latter date was supposed to be too young with respect to the age of overlying (32,5 ka BP) and underlying (39,6 ka BP) peat layers. Zagwijn (1974) dated a sedimentological and stratigraphical comparable sequence of undisturbed gyttja (36,6 ka BP on *Batrachium* seeds) overlying strongly involuted clayey peat of 38,4 ka BP at Hengelo.

In the southern Netherlands (Breda) Zagwijn (1993) described an exposure strongly resembling the Grouw and Hengelo sites in stratigraphy and age. An undisturbed, well-laminated clay-gyttja was found overlying an ice-wedge cast. The base of the clay-gyttja was dated at 37,000 ± 600 BP (GrN-2515), which shows that (shortly) before 37 ka BP permafrost conditions occurred in the southern Netherlands. The lowermost laminae of the clay-gyttja layer appeared to be involuted in the icewedge cast. This proves that melting of the ice wedge took place at the start of the clay-gyttja deposition, this is at 37 ka BP. The top of the gyttja layer was dated at 29,900 ± 460 BP (GrN-2141) which means that the lake environment persisted c. 7000 radiocarbon years. The ^{14}C-dates and general stratigraphy of the exposure Breda have previously been published by Van der Hammen et al. (1967). In accordance with Zagwijn (1993) we conclude that the clay-gyttja was formed in a lake environment during a slightly warmer period. The presence of an ice-wedge cast, directly below the lake sediments, suggests that the lake developed by permafrost degradation (thermokarst) at c. 37 ka BP.

All the dates presented above converge on an age for regional thaw-lake formation (permafrost degradation) and start of lake infilling between 38,4 and 37,8 ka BP. In the next paragraphs it will be argued that this phase of thaw-lake development was caused by an increase in temperature.

Climate-induced thermokarst lake formation

Thermokarst develops by the degradation of ice-rich permafrost (Mackay, 1992). The reasons for degradation may be local (river bank erosion, flooding, forest fire) or climatic (Burn & Smith, 1988). Once the ice is exposed to the sun or covered by water, melting continues until a new equilibrium is reached. This means that in exposures of the fossil periglacial record it is hard to distinguish between local and climate-induced thermokarst phenomena. A regional approach is necessary to separate local from regional changes. In this respect the study of Van Huissteden (1990, p. 127, Figure IX.4A and 4C) is important. He elaborated 212 ^{14}C-samples from Middle Pleniglacial sequences in the Netherlands, Belgium and northwestern Germany. His work shows a peak in peat occurrences around the 42-40 ka BP interval, followed by a gap in the peat frequency histogram between 39 and 37 ka BP. This gap resulted from omitting the available dates derived from gyttjas. From this line of reasoning it can be concluded that during the 39-37 ka BP period peat formation in (semi)terrestrial conditions was regionally replaced by gyttja deposition in lacustrine environments in the river valleys. In the Tilligte basin these gyttjas, although described from boreholes, often have an erosive lower boundary which meets the sedimentary characteristics of recent thaw lakes (Van Huissteden, 1990, pers. comm.). In combination with the established thermokarst phenomena for this period in exposures at Grouw and in the Hengelo basin the widespread deposition of gyttja may indicate that thaw lake environments became much more important, because of a change in climate.

Climate change during the Hengelo Interstadial

In the classical subdivision of the Weichselian Pleniglacial (Van der Hammen et al., 1967; Zagwijn, 1974) the 36-39 ka BP period is equivalent with the Hengelo Interstadial. The data presented above indicate an environmental change during this time interval. The regional increase of lakes in the Netherlands cannot be explained by intrinsic changes in the floodplains, such as channel migration, channel abandonment or backswamp formation. In our opinion a climatological change has induced the environmental changes leading to increased lake formation. The palaeobotanical record of unit h clearly indicates a temperature increase between 38,7 and 37,8 ka BP. Based on the presence or absence of specific temperature indicative species (Kolstrup, 1980) a summer temperature increase of 2°C is estimated. *Juniperus* attains maximal values in unit h pointing to the encroachment of the boreal forest boundary. A mean annual temperature around 12°C has been postulated. The presence of *Ceratophyllum* (indicative for a mean annual temperature of c. 13°C) in the lower part of the thaw lake infilling suggests that the climatic optimum of the Hengelo Interstadial was reached rather early in the sequence and probably was of short duration. This is in agreement with Kolstrup & Wijmstra (1977) who argued for a short climatic optimum (13-15°C) in the oldest part of the Hengelo Interstadial studied in sequence Bussloo.

In the final phase of lake infilling, shortly after 36,9 ka BP, a temperature drop of at least 3°C is registered by the disappearance of *Juniperus, Filipendula* and *Menyanthes*. In the Hengelo basin, a return to a strongly chinophilous (snow-dependant) vegetation, with *Salix herbacea* is registered in the top of the thermokarst fill (Ran et al., 1990: zone HGA-4). Also the Hengelo K.N.Z.

diagram, zone PWh3 (Zagwijn, 1974) shows an increase in *Salix* pollen. At Grouw the increase in *Empetrum* in the topmost sample may indicate a similar change towards a chinophilous shrub tundra vegetation. The increase in snow cover may have had implications for the water balance. An increase in snow melt water in late spring will have promoted peak discharges in the fluvial regime, a return to overbank deposition (unit i) and consequently, the termination of the lacustrine environment represented by unit h. Chronostratigraphically this interval, following the Hengelo Interstadial, should be correlated with part of the Huneborg Interval as described by Ran & Van Huissteden (1990) and which, according to these authors, should be characterized as cold and dry.

Speed of the climate changes

The dates presented here and those from previous investigations suggest a rapid temperature rise at the start of the Hengelo Interstadial. The youngest date of cryoturbated sediment underlying the Hengelo Interstadial is 38,4 ka BP (Zagwijn, 1974). The oldest date of thermokarst infilling is 37,8 ka BP (this study), which indicates that the temperature rise occurred in less than 600 radiocarbon years. The climate improvement of the Hengelo Interstadial did not last very long. The top of unit h (36,9 ka BP) already contains indications for a distinct cooling in the mean summer temperature (zone GrW-h3). The ^{14}C-dates (38,7-36,9 ka BP: this study; 38,4-36,6 ka BP: Zagwijn, 1974) point to less than 1800 radiocarbon years for the duration of the Hengelo Interstadial. This estimation agrees well with the 500 to 2000 radiocarbon years interstadials in the ice-core record of Greenland (Johnsen et al., 1992). According to Ran & Van Huissteden (1990) the Hengelo Interstadial was preceded by a cold phase (Hasselo Stadial: c. 40-39 ka BP). This would mean that stadial and interstadial conditions succeeded each other in less than c. 3500 radiocarbon years.

Effects of temperature rise on the permafrost and fluvial environment

The abundant presence of periglacial features (ice-wedge casts) in Grouw indicates the existence of continuous permafrost already before 43,3 ka BP, during the 43-35 ka BP period and later than 35 ka BP. The mean annual temperature, based on the presence of ice-wedge casts in silty subsoils, must have been around -4,5°C during these periods (Vandenberghe & Kasse, 1993; Vandenberghe & Pissart, 1993). The shrub tundra vegetation in the units d, f and k, indicates a mean summer temperature somewhat lower than 10°C. From these two estimates a winter temperature lower than -19°C can be calculated. However, generally the Middle Pleniglacial sequences in the Netherlands and Belgium do not display ice-wedge casts (Vandenberghe, 1985). This anomaly possibly points to a position of the Netherlands in the transition zone of the discontinuous and continuous permafrost during the Middle Pleniglacial, since ice wedges are normally associated with continuous permafrost (Vandenberghe & Pissart, 1993). The increase in temperature during the Hengelo Interstadial, maximally 5°C as suggested by Van der Hammen et al. (1967) and Zagwijn (1974), will have resulted in the disappearance of the continuous permafrost and a shift of the continuous-discontinuous permafrost boundary to the north. The melting of the ice-rich top of the permafrost will have been the cause for the increased thaw-lake formation during this phase. The lacustrine unit h is the reflection of this temporarily climatic improvement during the Hengelo Interstadial. According to Mackay (1992) increased thaw-lake formation can be ascribed to climatic warming. Maximum thaw-lake development along the present Western Arctic coast of Canada occurred between 9000 and 8000 BP during the postglacial climatic warming.

The decrease in permafrost distribution and increase in active layer thickness during the Hengelo Interstadial will have had an important impact on the hydrological cycle. The restoration of the groundwater recharge and the increased water storage capacity of the soil will have led to a more regular discharge of the river. This may explain the decrease in flooding of the overbank environment during the existence of the thermokarst lake in Grouw. The more regular discharge, as suggested here, is in contrast with Ran & Van Huissteden (1990) who proposed higher discharges and erosion during the Hengelo Interstadial, because of permafrost degradation.

The return of a chinophilous dwarfshrub vegetation shortly after 36,9 ka BP can be ascribed to the increasing importance of a snow cover. Together with the reestablishment of permafrost this will have led to increased peak discharges resulting in crevasse splay deposition (unit i). According to Mackay (1992) a climatic cooling may cause the (often catastrophic) drainage of thaw lakes. The formation of new ice wedges during a colder phase may lead to lake drainage along the easily erodible ice-wedge troughs. Also by thermal contraction in winter, lakes can drain along the interconnected ice-wedge cracks. Such a process of lake drainage by climatic cooling may have occurred also at the transition from unit h (thermokarst lake) to unit i (fluvial overbank deposition). Dehydration of the sediments of unit h would have increased its carying capacity and explains the absence of loading at the time of deposition of unit i.

Correlation of the Pleniglacial sequence with the ice-core record and inertia of the terrestrial geo- and ecosystems to climate change

The Weichselian Middle Pleniglacial has been correlated previously with oxygen isotope stage 3 (Vandenberghe, 1985; Behre & Van der Plicht, 1992). The ice-core record of Greenland (Summit ice core) reveals many major oxygen isotope fluctuations in this time interval corresponding with c. 16 interstadials (Johnsen et al., 1992; Dansgaard et al., 1993). The temperature increase of the Hengelo Interstadial may correspond with interstadial number 12 in stage 3 (Dansgaard et al., 1993).

In the continental record, however, only three or four interstadials have been recognized (Zagwijn, 1974; Behre & Van der Plicht, 1992). So the temperature fluctuations derived from the Greenland ice core are not or only partly reflected in the continental sedimentary record. Although there may have been swift climatic changes during the Middle Weichselian they are hardly registered in the vegetational record. The reason may be that the magnitude of the climatic changes was either too small to affect the tundra ecotone or the duration of the climatic improvement was too short for the vegetation zones to reach northern latitudes. The subzones within the tundra ecotone during this episode are thought to represent rather wide areas. Small shifts of these vegetation zones did not severely alter the vegetational composition for the Netherlands during the Middle Pleniglacial. The pollen diagrams indeed do show a fairly uniform vegetation pattern (Zagwijn, 1974; Ran, 1990). Furthermore, the continuous production of organic material throughout the entire Middle Pleniglacial (Van Huissteden, 1990) indicates that the landscape was covered with vegetation all the time.

The Middle Pleniglacial fluvial sediments also show a remarkable sedimentological uniformity, pointing to a uniform depositional environment in this period (Ruegg, 1975; De Gans, 1981; Van Huissteden, 1990). In our opinion most of the lithological changes in the Middle Pleniglacial sequences can be attributed to local hydrological changes, instead of climate changes. The Middle Pleniglacial rivers hardly responded to the short-term climatic changes, predominantly because the stabilizing vegetation cover remained more or less the same. The thresholds for river pattern changes were probably never exceeded in the Middle Pleniglacial. The river type can best be described as anastomosing, in contrast with the Late Pleniglacial when polar desert conditions led to a braiding river style (Van Huissteden, 1990). The Hengelo Interstadial climatic amelioration may have resulted in discharge changes in the river, but it did not affect the overall channel morphology. Lake environments, on the other hand, regionally increased in area during the Hengelo Interstadial, because of widespread permafrost degradation and thaw lake development.

Conclusions

A detailed sedimentological, palynological and chronostratigraphical analysis of a Weichselian Middle Pleniglacial sequence at Grouw (northern Netherlands) provided new insights concerning the biotic and abiotic environment during the 43-35 ka BP period. These are summarized as follows:

1. The 43-35 ka BP time interval provides evidence (=levels of ice-wedge casts) for several phases of permafrost, pointing to a mean annual temperature around -4,5°C. The mean summer temperature, based on the palaeobotanical record, during most of the 43-35 ka BP interval could be established at or slightly below 10°C. The mean winter temperature is estimated to have been lower than -19°C.
2. The Middle Pleniglacial river system was characterized by strongly episodic flow, attributed to spring snow melt. The channel facies reveals reactivation surfaces and alternating sand-silt bedding formed by falling water and rapid water level fluctuations.
3. Shallow fluvial crevasse splay, backswamp and lake deposits constitute the overbank facies. Permafrost development and degradation in the overbank environment is closely related to the sedimentary cyclicity.
4. In the absence of clear climatic oscillations, most of the changes in the Middle Pleniglacial fluvial periglacial environment can be explained by intrinsic factors.
5. Ice-wedge casts, cryoturbations and subsequent thaw-lake deposition point to rapid climate changes from full stadial to interstadial conditions between 38,7 and 37,8 ka BP correlating with the Hengelo Interstadial. A mean summer temperature rise from 10 to 12°C has been deduced from the continuous presence of juniper in the thaw-lake sediment.
6. The Hengelo Interstadial lasted less than 1800 radiocarbon years (38,7-36,9 ka BP). Its termination at c. 36,9 ka BP is characterized by a summer temperature drop from 12 to 8°C and a return of chinophilous taxa.
7. The regional occurrence of thaw lake environments during the Hengelo Interstadial implies a northward shift of the continuous-discontinuous permafrost boundary.
8. The climatic improvement, responsible for the disappearance of the permafrost during the Hengelo Interstadial, resulted in a more regular river discharge by an increased water storage capacity of the soil.
9. The thresholds for major changes in river pattern and vegetation were not exceeded during the Middle Pleniglacial. Climatic changes are reflected only by a regional increase of lake environments.

References

Behre, K.-E., & Van der Plicht, J., 1992: Towards an absolute chronology for the last glacial period in Europe: radiocarbon dates from Oerel, northern Germany. - Veget. Hist. Archaeobot., 1, p. 111-117.

Bohncke, S.J.P., & Vandenberghe, J., 1991: Palaeohydrological development in the southern Netherlands during the last 15000 years. - In: Starkel, L., Gregory, K.J. & Thornes, J.B. (eds): Temperate palaeohydrology, p. 253-281. - John Wiley and Sons, Chichester.

Brinkkemper, O., Van Geel, B., & Wiegers, J. 1987: Palaeoecological study of a Middle-Pleniglacial deposit from Tilligte, The Netherlands. - Rev. Palaeobot. Palynol., 51, p. 235-269.

Burn, C.R., & Smith, M.W., 1988: Thermokarst lakes at Mayo, Yukon Territory, Canada. - Proc. Vth Intern. Conference on Permafrost, Trondheim, p. 700-705.

Chernov, YU.I., 1980: The living tundra (English translation by D. Løve, 1985). - Cambridge University Press, 213 pp.

Cnossen, J., & Zandstra, J.G., 1965: De oudste Boorneloop in Friesland en veen uit de Paudorftijd nabij Heerenveen. - Boor en Spade, XIV, p. 62-87.

Collinson, J.D., 1970: Bedforms of the Tana River, Norway. - Geografiska Annaler, 52A, p. 31-56.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahl-Jensen, D., Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjörnsdottir, A.E., Jouzel, J., & Bond, G., 1993: Evidence for general instability of past climate from a 250-kyr ice-core record. - Nature, 364, p. 218-220.

De Gans, W., 1981: The Drentsche Aa valley system. - Thesis, Vrije Universiteit Amsterdam, 132 pp.

De Groot, T.A.M., Van Adrichem Boogaert, H.A., Fischer, M.M., Klijnstra, B., Van Montfrans, H.M., Uil, H., Ter Wee, M.W., Van Weperen, M.J., Zandstra, J.G., e.a., 1987: Toelichtingen bij de geologische kaart van Nederland 1:50.000, Blad Heerenveen West (11W) en Blad Heerenveen Oost (11O). - Rijks Geol. Dienst, Haarlem, 251 pp.

Ehlers, J., Meyer, K.D., & Stephan, H.J., 1984: The pre-Weichselian glaciations of north-west Europe. - Quaternary Science Reviews, 3, p. 1-40.

Faegri, K., & Iversen, J., 1975: Textbook of pollenanalysis. - Munksgaard, Copenhagen, 295 pp.

Hopkins, D.M., & Kidd, J.G., 1988: Thaw lake sediments and sedimentary environment. - Proc. Vth Intern. Conference on Permafrost, Trondheim, p. 790-795.

Iversen, J., 1954: The Late-Glacial flora of Denmark and its relation to climate and soil. - Danmarks Geologiske Undersgelse, II Raekke, 80, p. 87-119.

Iversen, J., 1973: The development of Denmark's nature since the Last Glacial. - Danmarks Geologiske Undersøgelse V. Raekke, Nr. 7-C, C.A. Reitzels Forlag, København, 126 pp.

Johnsen, S.J., Clausen, H.B., Dansgaard, W., Fuhrer, K., Gundestrup, N., Hammer, C.U., Iversen, P., Jouzel, J., Stauffer, B., & Steffensen, J.P., 1992: Irregular glacial interstadials recorded in a new Greenland ice core. - Nature, 359, p. 311-313.

Jones, C.M., 1977: Effects of varying discharge regimes on bed-form sedimentary structures in modern rivers. - Geology, 5, p. 567-570.

Kasse, C., Vandenberghe, J., & Bohncke, S., 1994: Climatic change and fluvial dynamics of the Maas during the late Weichselian and early Holocene. - Paläoklimaforschung (in press).

Kolstrup, E., 1980: Climate and stratigraphy in northwestern Europe between 30,000 BP and 13,000 BP, with special reference to The Netherlands. - Meded. Rijks Geol. Dienst, 32, p. 181-253.

Kolstrup, E., 1990: The puzzle of Weichselian vegetation poor in trees. - Geol. en Mijnbouw, 69, p. 253-262.

Kolstrup, E., & Wijmstra, T.A., 1977: A palynological investigation of the Moershoofd, Hengelo and Denekamp Interstadials in the Netherlands. - Geol. en Mijnbouw, 56, p. 85-102.

Lowe, J.J., & Walker, J.C., 1977: The reconstruction of the Lateglacial environment in the southern and eastern Grampian Highlands. - In: Gray, J.M., & Lowe, J.J. (eds): Studies in the Scottish Lateglacial Environment, p. 101-118. - Pergamon, Oxford.

Mackay, J.R., 1992: Lake stability in an ice-rich permafrost environment: examples from the western Arctic coast. - In: Robarts, R.D., & Bothwell, M.L. (eds): Aquatic ecosystems in semi-arid regions: implications for resource management, p. 1-26. - N.H.R.I. Symposium Series 7, Environment Canada, Saskatoon.

McKee, E.D., Crosby, E.J., & Berryhill JR, H.L., 1967: Flood deposits, Bijou Creek, Colorada, June 1965. - J. Sed. Petr., 37, p. 829-851.

Mennington, W., 1977: Lake sediments and Lateglacial environment in Northern Scotland. - In: Gray, J.M., & Lowe, J.J. (eds): Studies in the Scottish Lateglacial Environment, p. 119-141. Pergamon, Oxford.

Ran, E.T.H., 1990: Dynamics of vegetation and environment during the Middle Pleniglacial in the Dinkel valley (The Netherlands). - Meded. Rijks Geol. Dienst, 44, p. 139-205.

Ran, E.T.H., Bohncke, S.J.P., Van Huissteden, J., & Vandenberghe, J., 1990: Evidence of episodic permafrost conditions during the Weichselian Middle Pleniglacial in the Hengelo Basin (The Netherlands). - Geol. en Mijnbouw, 69, p. 207-218.

Ran, E.T.H., & Van Huissteden, J., 1990: The Dinkel valley in the Middle Pleniglacial: dynamics of a tundra river system. - Meded. Rijks Geol. Dienst, 44, p. 209-220.

RGD, 1991a: Rapport no. 1122: Uitkomsten van een C14-bepaling aan materiaal afkomstig uit de bouwput voor de aanleg van een tunnel onder het Margrietkanaal te

Grouw (zuidzijde). - Rijks Geol. Dienst, Afdeling Paleobotanie Kenozoïcum, Haarlem.

RGD, 1991b: Rapport no. 1123: Uitkomsten van een C14-bepaling aan materiaal verkregen uit de bouwput voor de aanleg van een tunnel onder het Prinses Margrietkanaal te Grouw (noordzijde). - Rijks Geol. Dienst, Afdeling Paleobotanie Kenozoïcum, Haarlem.

Ruegg, G.H.J., 1975: Sedimentary structures and depositional environments of Middle- and Upper-Pleistocene glacial time deposits from an excavation at Peelo, near Assen, The Netherlands. - Meded. Rijks Geol. Dienst, N.S. 26, p. 17-37.

Ruegg, G.H.J., 1983: Periglacial eolian evenly laminated sandy deposits in the Late Pleistocene of NW Europe, a facies unrecorded in modern sedimentological handbooks. - In: Brookfield, M.E. & Ahlbrandt, T.S. (eds): Eolian sediments and Processes (Developments in Sedimentology 38), p. 455-482. - Elsevier, Amsterdam.

Rust, B.R., 1972: Structure and process in a braided river. - Sed., 18, p. 221-245.

Schlager, W., 1993: Accommodation and supply - a dual control on stratigraphic sequences. - Sed. Geol., 86, p. 111-136.

Schwan, J., 1986: The origin of horizontal alternating bedding in Weichselian aeolian sands in northwestern Europe. - Sed. Geol., 49, p. 73-108.

Vandenberghe, J., 1985: Paleoenvironment and stratigraphy during the last glacial in the Belgian-Dutch border region. - Quaternary Research, 24, p. 23-38.

Vandenberghe, J., & Krook, L., 1981: Stratigraphy and genesis of Pleistocene deposits at Alphen (southern Netherlands). - Geol. en Mijnbouw, 60, p. 417-426.

Vandenberghe, J., & Krook, L., 1985: La stratigraphie et la genèse de dépôts Pleistocènes à Goirle (Pays-Bas). - Bull. de l'Assoc. Franç. pour l'étude du Quatern., 22, p. 239-247.

Vandenberghe, J., Mücher, H., Roebroeks, W., & Gemke, D., 1985: lithostratigraphy and palaeoenvironment of the Pleistocene deposits at Maastricht-Belvédère. - Meded. Rijks Geol. Dienst, 39, p. 7-18.

Vandenberghe, J., & Kasse, C., 1993: Periodic ice-wedge formation and Weichselian cold-climate floodplain sedimentation in the Netherlands. - Proc. Sixth Intern. Conference on Permafrost, Beijing, p. 643-647.

Vandenberghe, J., Mommersteeg, H., & Edelman, D., 1993: Lithogenesis and geomorphological processes of the Pleistocene deposits at Maastricht-Belvédère. - Meded. Rijks Geol. Dienst, 47, p. 7-17.

Vandenberghe, J., & Pissart, A., 1993: Permafrost changes in Europe during the last glacial. - Permafrost and Periglacial Processes, 4, p. 121-135.

Van der Hammen, T., 1951: Late-Glacial flora and periglacial phenomena in the Netherlands. - Leidse Geol. Meded., 17, p. 71-183.

Van der Hammen, T., Maarleveld, G.C., Vogel, J.C., & Zagwijn, W.H. 1967: Stratigraphy, climatic succession and radiocarbon dating of the last glacial in the Netherlands. - Geol. en Mijnbouw, 46, p. 79-95.

Van Geel, B., Bohncke, S.J.P., & Dee, H., 1981: A palaeoecological study of an upper Late Glacial and Holocene sequence from "De Borchert", The Netherlands. - Rev. Palaeobot. Palynol., 31, p. 367-448.

Van Huissteden, J., 1990: Tundra rivers of the last glacial: sedimentation and geomorphological processes during the Middle Pleniglacial in Twente, eastern Netherlands. - Meded. Rijks Geol. Dienst, 44, p. 1-138.

Zagwijn, W.H., 1974: Vegetation, climate and radiocarbon datings in the Late Pleistocene of The Netherlands. - Meded. Rijks Geol. Dienst, N.S. 25, p. 101-111.

Zagwijn, W.H., 1993: Palaeobotanisch onderzoek van ontsluiting Rioolsleuf Breda (Viscosewijk). - Rapport 1219, Rijks Geol. Dienst, Palaeobotanisch Laboratorium, Haarlem, p. 1-9